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GEORGE C. MARSHALL SPACE FLIGHT CENTER

THE DEVELOPMENT OF A SOLAR RESIDENTIAL HEATING AND COOLING SYSTEM

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THE DEVELOPMENT OF A SOLAR RESIDENTIAL HEATING AND COOLING SYSTEM

GEORGE C. MARSHALL SPACE FLIGHT CENTER
MARSHALL SPACE FLIGHT CENTER, ALABAMA

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THE DEVELOPMENT OF A SOLAR RESIDENTIAL HEATING AND COOLING SYSTEM

SUMMARY

This report describes the Marshall Space Flight Center (MSFC) solar heating and cooling facility and presents a discussion of test results obtained from late May 1974 to September 1974. During this period the system was operated in the cooling mode only, since no heating was required. System operation is continuing and data are being gathered for operation of the system in the heating mode.

The MSFC facility was assembled to demonstrate the engineering feasibility of utilizing solar energy for heating and cooling buildings. The primary purpose of the facility is to provide an engineering evaluation of the total system and the key subsystems and to investigate areas of possible improvement in design and efficiency. The system has not been optimized, and this should be considered when reviewing the energy balances presented in this report.

As will be shown, considerable information is being obtained from operation of the system and significant improvements in operation and efficiency are being achieved.

The basic solar heating and cooling system utilizes a flat plate solar energy collector, a large water tank for thermal energy storage, heat exchangers for space heating, and an absorption cycle air conditioner for space cooling. A complete description of all systems is given in Section II.

Development activities for this test system have included assembly, checkout, operation, modification, and data analysis, all of which are discussed herein. System operation is continuing, and additional modifications will be made as necessary to support continuing system improvements and upgrading of performance evaluation techniques.

Selected data analyses for the first 15 weeks of testing are included herein. Findings associated with energy storage and the energy storage system are also outlined and conclusions resulting from test findings are provided.

An evaluation of the data for summer operation indicates that the current system is capable of supplying an average of 50 percent of the thermal energy required to drive the air conditioner. Preliminary evaluation of data collected for operation in the heating mode during the winter indicates that nearly 100 percent of the thermal energy required for heating can be supplied by the system.

I. INTRODUCTION

Among the possible alternative energy sources to fossil fuels, solar energy is possibly the most pollution free, nondepletable source. It may be expected that the sun will ultimately be harnessed to produce electricity, synthetic liquid and gaseous fuels, and high temperature thermal energy for industrial processes. However, the most immediately realizable application of solar energy will be to heat and cool buildings, since this application will require the fewest technological advances with the least expenditures of time and money.

Currently, a major obstacle to widespread use of solar energy for heating and cooling is the initial cost of the system. The design of the system discussed herein uses conventional construction techniques and materials; however, performance, cost, and energy savings were not optimized. In addition a number of subsystems (e.g., the solar collector) are custom made in small lots which results in material and labor costs that are not representative of production hardware. For these reasons cost data for this facility are not relevant to future marketable systems and are therefore not presented.

Efforts are currently underway at Marshall Space Flight Center to investigate the performance of a solar heating and cooling system. This report describes those activities to date and presents the results of tests conducted during the summer of 1974. Activities associated with fabrication and preliminary testing on the solar house located at MSFC are described. In addition selected test data are presented and a number of conclusions are provided.

The major design and fabrication effort extended from September 1973 through May 1974. Development testing began on May 28, 1974. These tests consisted of full system operation in the cooling mode only. Testing on the originally designed system lasted through most of June. Normal testing was interrupted by a series of special air conditioner tests in late June which continued through mid-July. These tests were followed by system modifications based on test findings. Finally, from late July through August, the modified system was tested in the air conditioning mode. Testing is continuing through the winter to obtain data on system operation in the heating mode.

The objectives of these early tests were to:

1. Assemble a solar heating and cooling facility using existing materials, equipment, and assembly methods.

2. Operate the facility for checkout and development testing purposes.

3. Analyze test data to establish system operational characteristics and to evaluate performance while defining any required modifications.

4. Modify the system where feasible to improve system performance within the framework of hardware available and schedule constraints.

5. Perform additional testing to allow evaluation of modifications.

II. FACILITY DESCRIPTION

A. General

The system and subsystem descriptions and control logic given in this section represent the original configurations that were effective at the time of test initiation on May 28, 1974. All significant subsequent alterations are discussed in applicable paragraphs of Section III.

The solar facility (Figs. II-1 and II-2) is located on the MSFC complex adjacent to Building 4619, at the corner of Rideout and Fowler roads. Three house trailers have been joined to form a single habitable structure. The test system is composed of the solar collector, an absorption air conditioning system with its associated cooling tower, a hot water heat exchanger for winter operation, a water tank for energy storage, and the habitable quarters (Figs. II-2 and II-3). These major subsystems are interconnected by a system of water pipes. The control network is fully automated to allow continuous operation.

A simplified operational description of the system follows, and detailed descriptions of the various subsystems and evaluations of their performance are provided in subsequent subsections.

B. Operational Description

As the sun heats the solar collector, water flowing through the tubes in the collector is heated. This hot water is returned to the energy storage tank. When the home thermostat requires either heating or cooling, hot water is directed from the storage tank to a three-way valve that diverts flow to eithe the heater or air conditioner. In the cooling mode hot water is used to powe a 3-ton absorption air conditioner. Air from the house is blown over the col air conditioner coils from which it is directed via ducting into the individual rooms of the house. In the event water from the storage tank is not sufficier hot to activate the air conditioner, the water temperature is elevated to an acceptable level by auxiliary heaters. In the heating mode the hot water sin passes through a heating coil. In the event the water is too cool to provide sufficient heating, duct electrical resistance (strip) heaters activate to warn the air directly. The same blower used to circulate air across the cooling c provides flow for the heating coil/heater combination. In both modes the thermostat is the central control device used to activate the automatic fluid

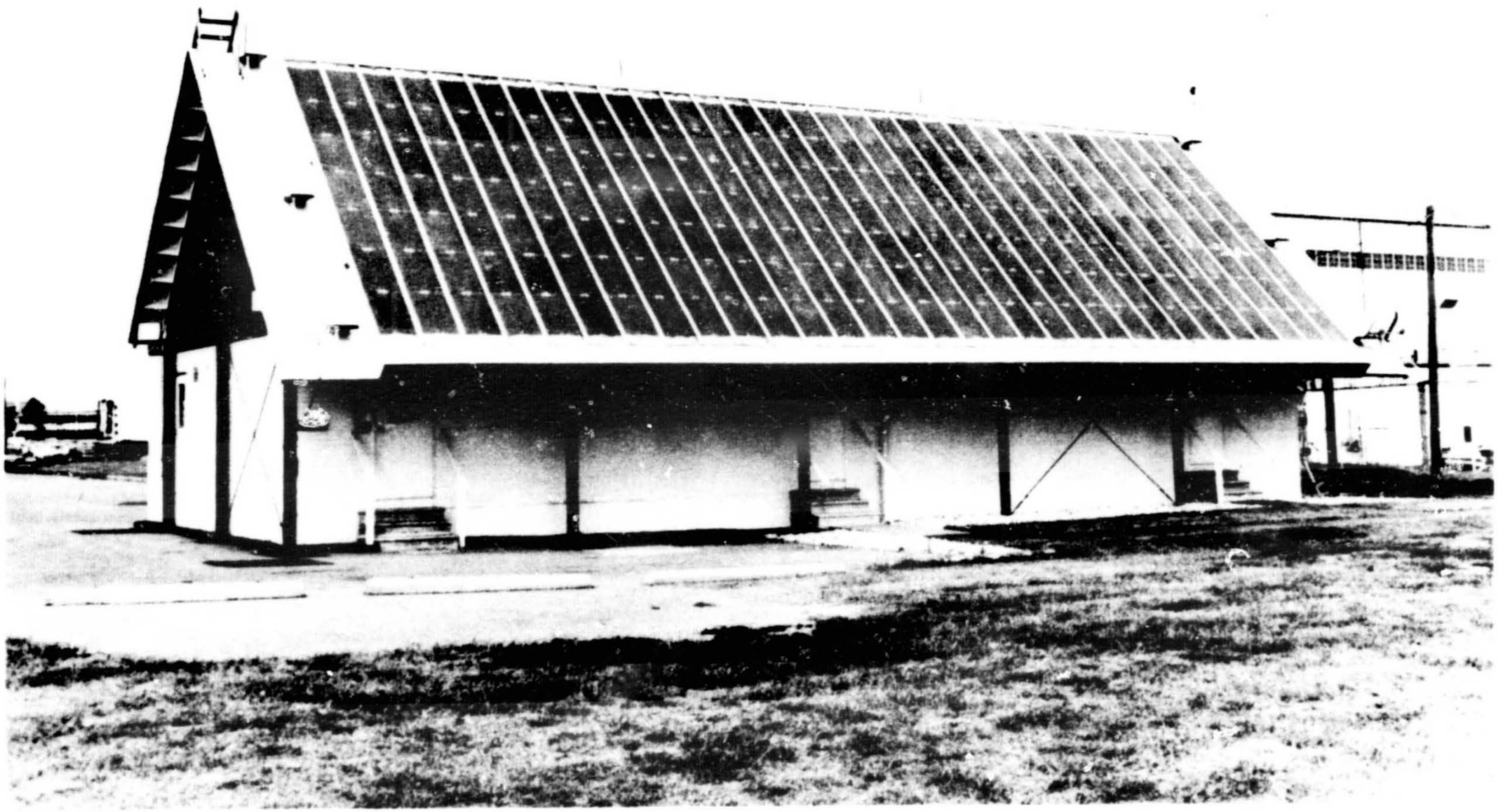

Figure II-1. Photograph of solar house.

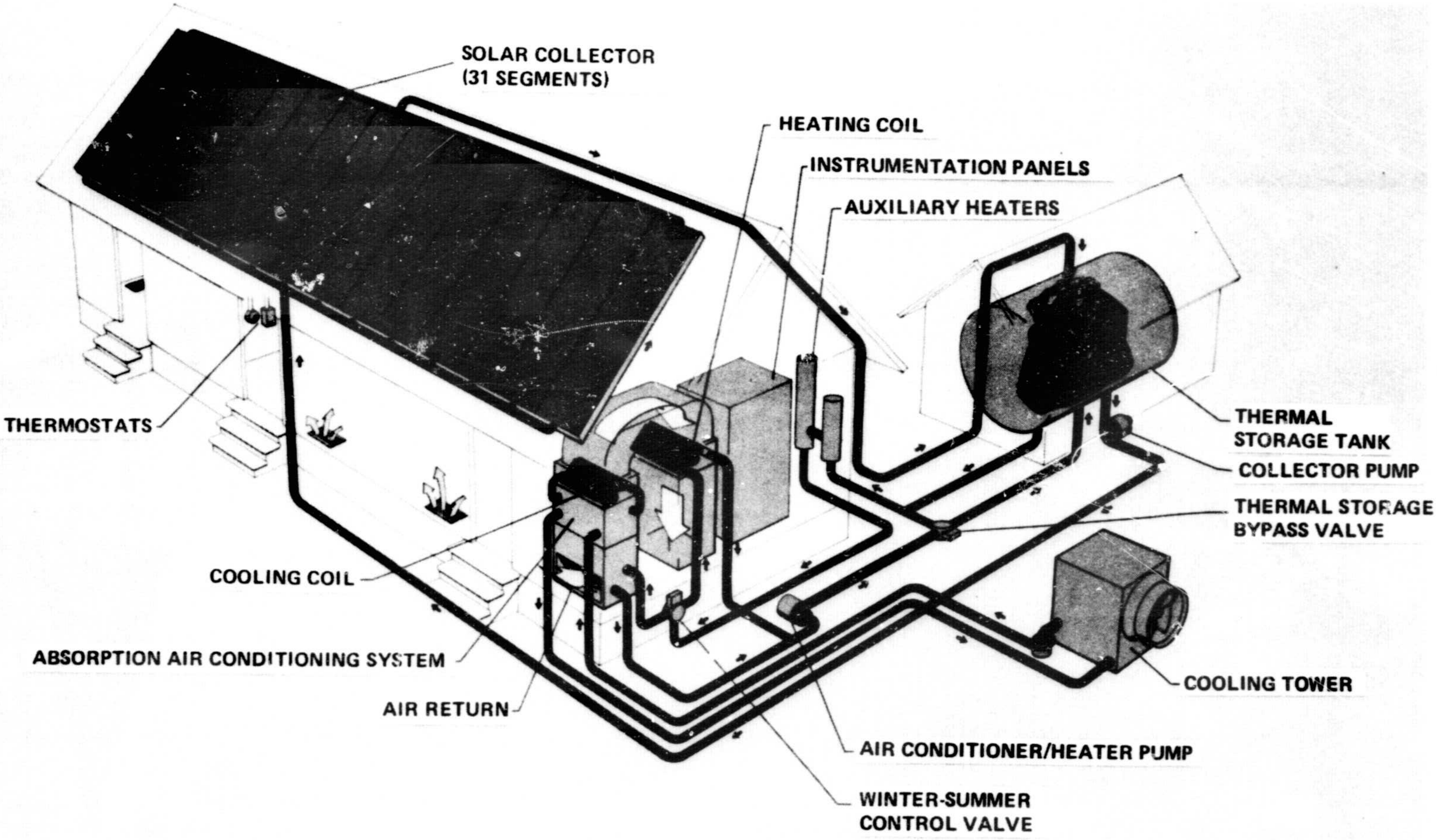

Figure II-2. MSFC solar house site schematic.

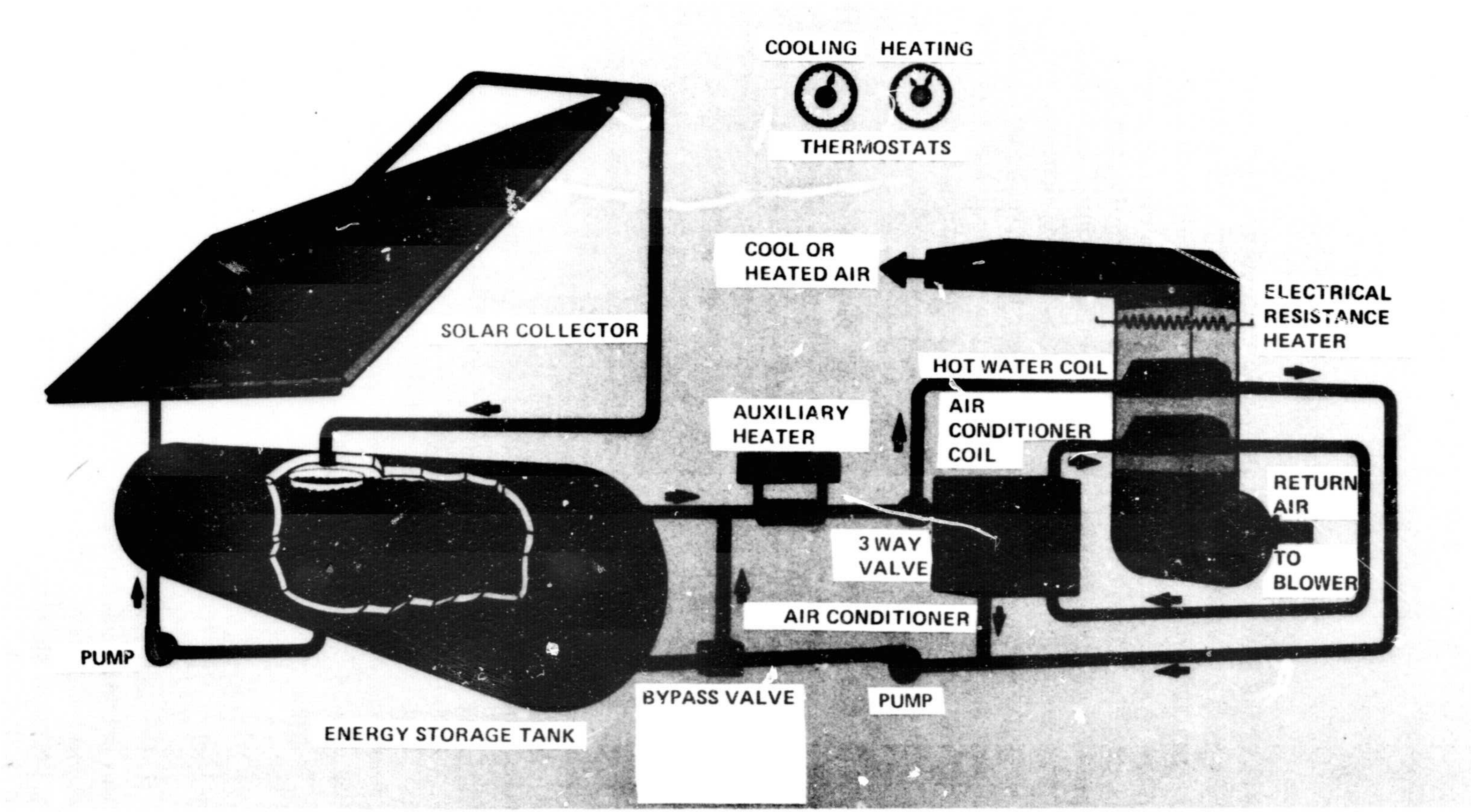

Figure II-3. Simplified system schematic.

control system. The collector control system is also automatically activated and deactivated based on various logic parameters that will be discussed in a subsequent subsection.

C. Solar Collector

The heart of the test system is the solar collector. Although the projected area of the roof covered by the collector is 1475 ft^2, the collector module surface area is only 1302 ft^2. Because of edge shading only a 1218-ft^2 maximum solar field-of-view is possible from the collector (this excludes shadowing by the wire matrix used to support the Tedlar cover). The collector is situated on the south side of a 45-deg pitched roof with a clear unobstructed view of the southern sky. The collector consists of 31 segments; each segment (Fig. II-4) consists of an aluminum tray containing 7 collector heat exchangers joined in series. These heat exchangers are fabricated from 1100 series aluminum sheets. The heat exchangers are roll-bond type panels formed from two sheets that have been bonded together and expanded in selected areas to form water passages (Fig. II-5.). Each heat exchanger is 2 ft by 3 ft in overall size. The heat exchanger surfaces are electroplated with a black nickel material, which has initial approximate solar absorptance and thermal emittance properties of 0.92 and 0.06, respectively. Figure II-6 presents the acceptance criteria used along with a number of actual data points. Although the MSFC black nickel coating has excellent collector initially applied coating properties, it is unstable in the presence of moisture. For this reason, an active purge is incorporated in the collectors to shield the coating from high ambient humidities. The backs of the heat exchangers are insulated using 6 in. thick household-type fiberglass battens.

The coated outer face of the heat exchangers is covered with wire-reinforced Tedlar plastic. The Tedlar allows transmission of solar energy while retarding convective heat losses from the coated collector surface of the heat exchanger. The Tedlar cover also provides a "greenhouse" effect by trapping solar energy. An added benefit of this cover is the protection it provides against the effects of dust, sand, hail, snow, ice, and other possibly damaging matter. The Tedlar cover is composed of a single 2-mil sheet covering 27 of the 31 segments. The last four segments on the east end of the roof are covered with 4-mil Tedlar. The supporting wire is 0.105 in. diameter galvanized iron (i.e., common welded fence wire) forming 2 in. by 4 in. grids.

The collector heat exchangers are held in the aluminum trays by wooden strips that form channels on two sides of the exchangers. Teflon clips prevent the edges of the heat exchangers from touching the sides of the aluminum trays, thus preventing thermal shorts. The assembled collector weight is approximately 4600 lb, adding 10 percent to the normal roof loading.

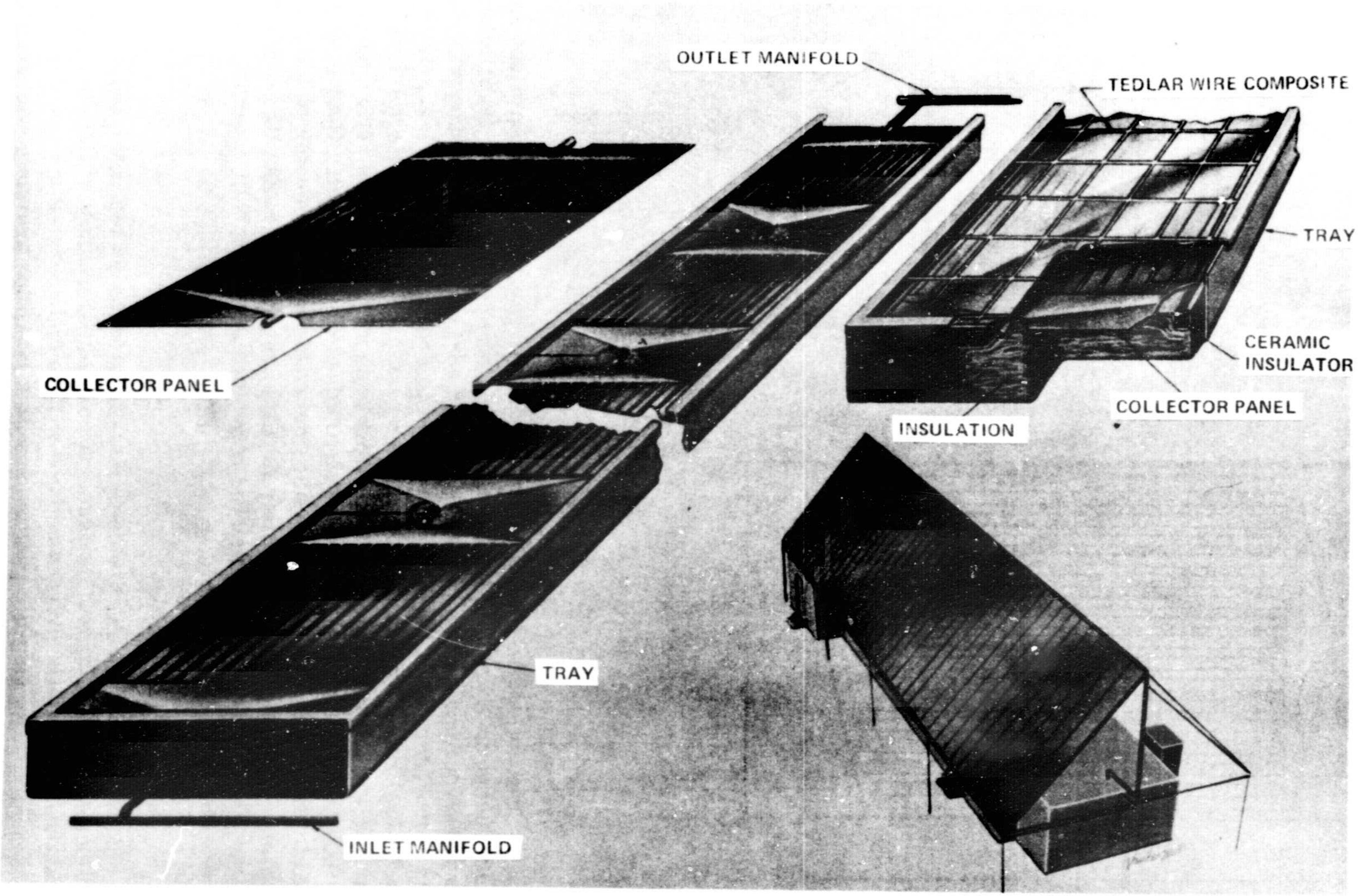

Figure II-4. MSFC collector design features.

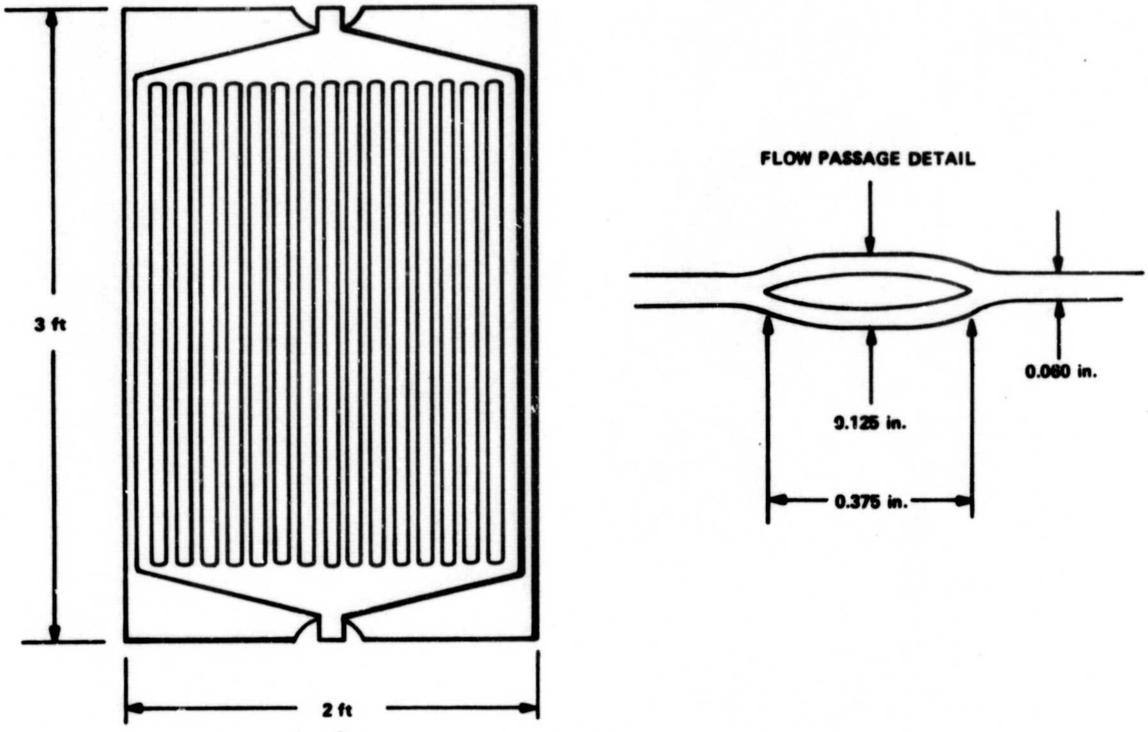

Figure II-5. Roll-bond panel design.

D. Collector Purge

The collector is provided with a dry air purge system to protect the black nickel coating which automatically maintains the humidity level between 15 and 40 percent relative humidity.[1] Two surplus Skylab life support system gas compressors are mounted in parallel to provide a 30 cfm (i.e., 15 cfm each) flow rate capability. The moist return air from the collector flows into a desiccant bed which absorbs the water from the gas stream returning the dried air to the inlet manifold located adjacent to the collector fluid inlet manifold. The purge gas enters the collector assembly in the center of the insulation portion of the segment. A similar manifold returns the moist air from the top of the collector at the roof apex to the desiccant/compressor assembly located under the roof.

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1. Significant advances have been made in breadboard testing in the area of collector humidity control devices. A completely passive system has been designed and satisfactorily tested and will be incorporated in a second generation collector for long life evaluation with a resulting system power reduction.

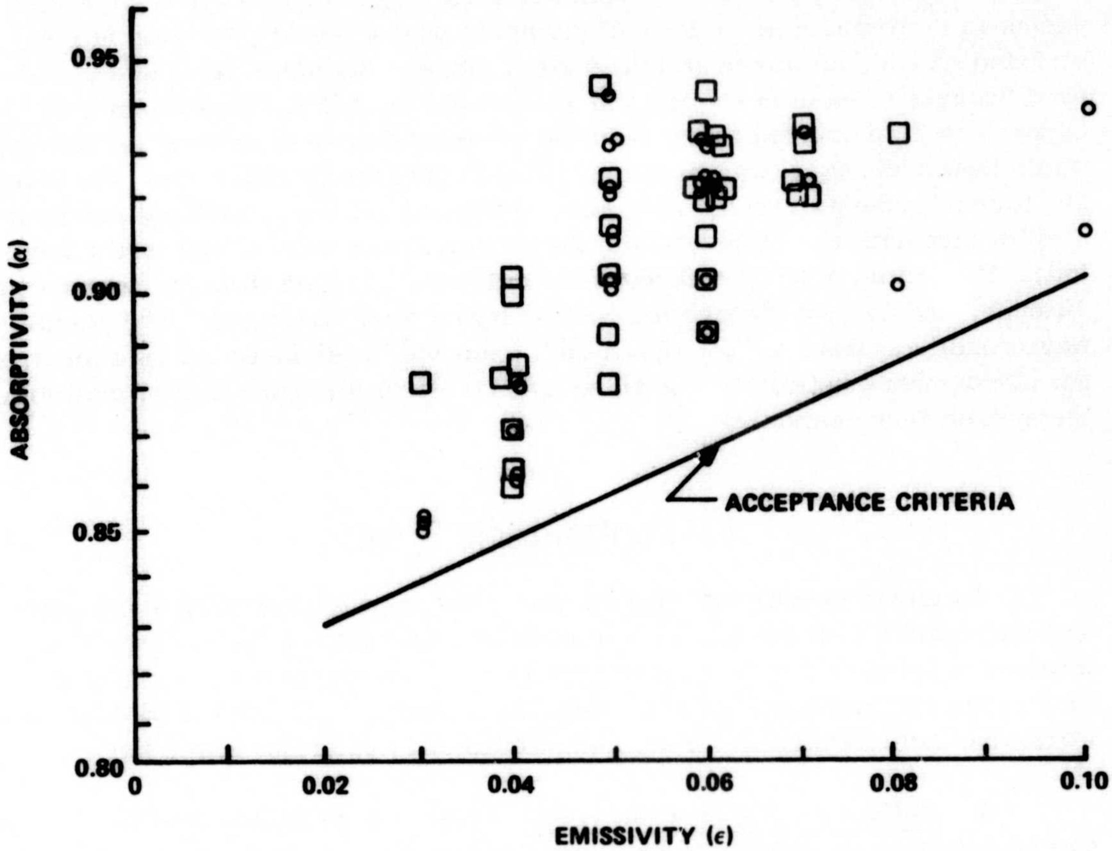


Figure II-6. MSFC collector coating acceptance criteria.

E. Piping System

The interconnecting piping system basically consists of two hot water loops; the collector and air conditioner/heater (AC/Htr) loops, which are actually common since they both return to the water tank, and the cold water loop, which connects the cooling tower to the air conditioner. The collector loop contains a 1/3-hp centrifugal pump that circulates deionized water having approximately 750 ppm by weight sodium chromate additive for inhibiting corrosion. Water is circulated from the tank to the collector inlet manifold. From the inlet manifold, the total water flow is evenly divided between the 31 segments, returned to a common outlet manifold, and then to the water tank.

All piping with the exception of the collector heat exchangers, which are aluminum, and the AC/Htr plumbing in the trailer area, which is stainless steel, are made of galvanized iron. The collector supply and return lines are

2 in. in diameter. The AC/Htr loop has 1 in. diameter galvanized iron pipe except in the immediate vicinity of the house where the AC/Htr loop is constructed of 1 in. diameter stainless steel tubing. Stainless steel tubing was used because of ease in routing and availability at MSFC. Chromium and copper are also present in the fluid loop in the AC control valving and the hot water heat exchanger, respectively. The cooling tower supply and return lines are formed from galvanized iron pipe. Identical 1/2-hp centrifugal pumps are used to circulate fluid through both the cooling tower and AC/Htr water loops. Initial flow rates of 31 gpm through the collector, 11 gpm through the air conditioner, and 10 gpm through the cooling tower were baselined. The pumps were readily available, "off-the-shelf", "low bid" equipment and as such are not performance optimized. Also no special effort was expended in minimizing the system flow resistance.

F. Control/Logic System

An electromechanical logic system was used to control flow initiation and termination to the collector. Similar systems were used to protect the water tank from inadvertent overpressurization and to control fluid and gas flow in the air conditioning and cooling tower loops. Automatic flow bypasses were also incorporated in the air conditioner and heater hot water loop.

1. Collector/Energy Tank Loop. Before the collector loop water pump can be activated, a number of logic checks must be satisfied. The water tank ullage pressure must be less than 25 psig and the collector surface temperature cannot exceed 250° F. In the automatic mode, if the two previous conditions were satisfied and the collector surface temperature was at least 5° F greater than the water tank temperature but not more than 50° F greater, the collector pump would activate for 5 minutes. However, if at any time one of the first two conditions failed to be satisfied or, after the 5-minutes have elapsed, any of the last two conditions are violated, the pump operation will terminate automatically. To operate the pump in the manual mode only the first two conditions must be satisfied. Figure II-7 depicts a flow diagram of this logic.

A protection system in the water tank forces the tank vent valve open above 30-psig ullage pressure (Fig. II-8).

2. Air Conditioner/Heater Loop. In the air conditioning loop, the cooling mode is selected manually by proper positioning of a switch on the thermostat. The selection of the cooling mode positions a three-way valve allowing hot flow to the air conditioner. In the event the water returning to the water tank from the air conditioner is warmer than the tank water, a tank bypass

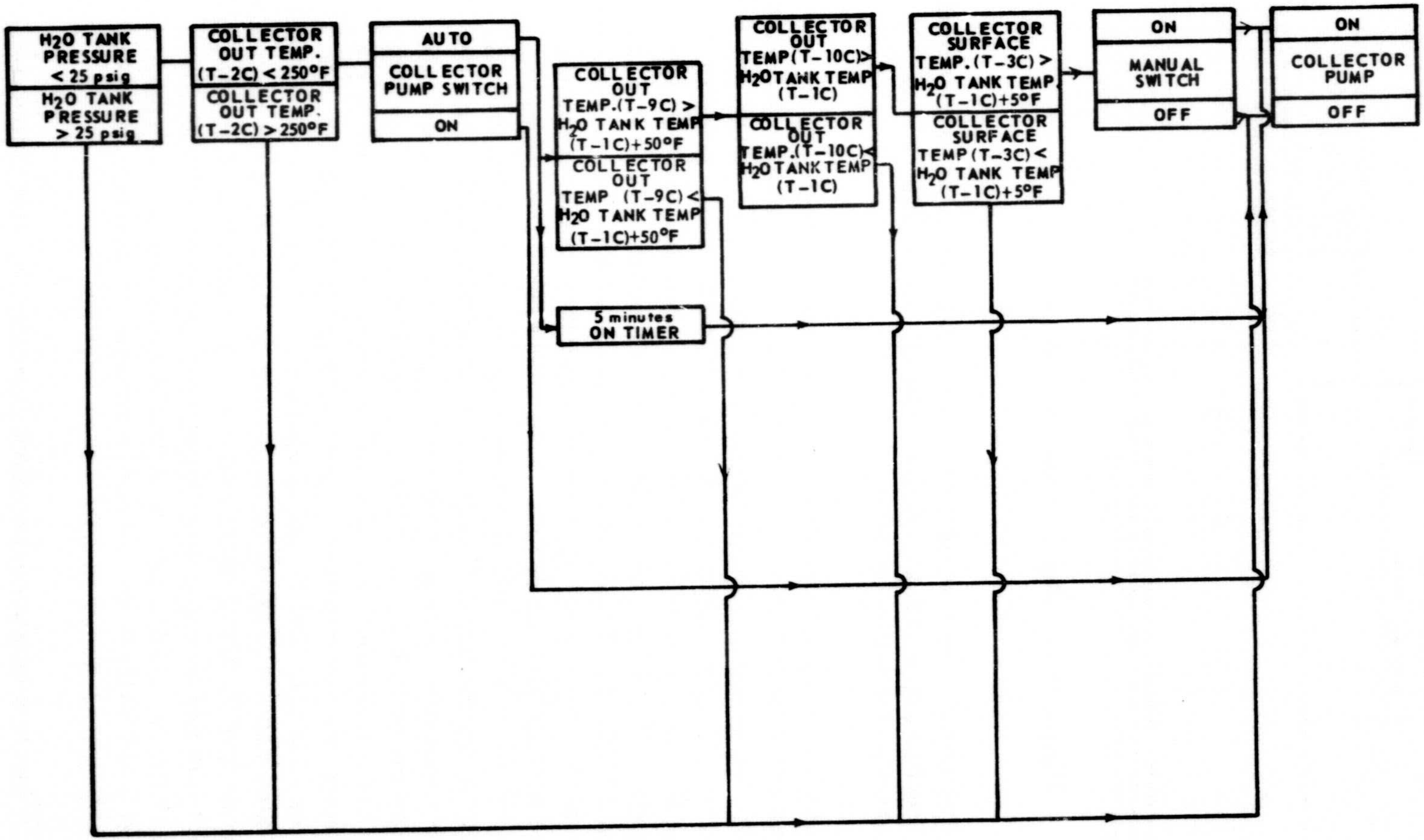
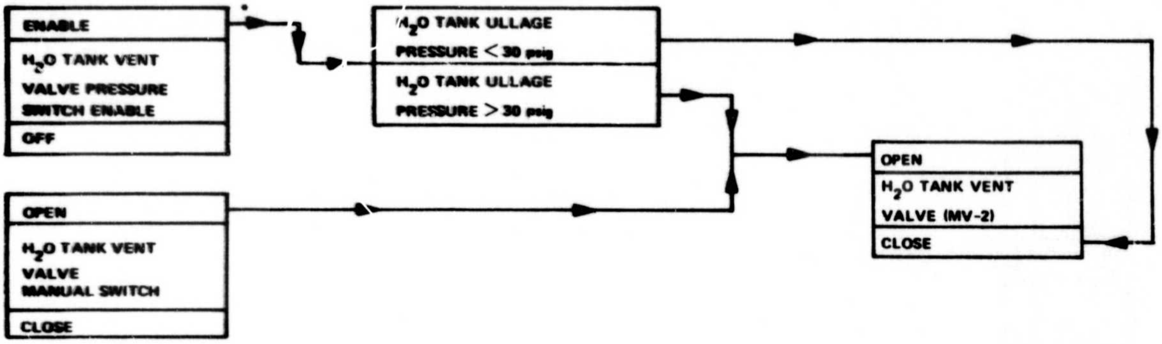


Figure II-7. Collector loop logic.



*MANUAL SWITCH MUST BE OFF BEFORE ENABLING PRESSURE SWITCH CONTINUOUSLY BECAUSE IT IS POSSIBLE TO POWER BOTH SIDES OF THE VALVE SIMULTANEOUSLY. ALSO, PRESSURE SWITCH MUST BE DISABLED BEFORE MANUAL OPERATION.

Figure II-8. Energy storage tank logic.

valve automatically diverts flow around the water tank to the water heater inlet. In this mode, all the heating necessary to drive the air conditioner comes from two electrically powered hot water heaters.

When the thermostat inside the dwelling is set on the cooling cycle and air temperature within the dwelling increases to the upper thermostat set point, the system is activated as follows (Fig. II-9). The cooling tower pump and fan and the air conditioner fan are energized, the air conditioner loop pump is energized and supplies 11 gpm of water to the system (flow is preset by hand valves HV-11 and HV-12), and hot water then passes through a filter into two heaters (HTR-1 and HTR-2). These heaters are used to either provide all the energy necessary in the tank bypass mode or to supplement energy from the storage tank in the storage tank mode (see paragraph F.4). The hot water then flows into motor valve MV-3 which, on the summer thermostat setting, directs 100 percent of the hot water flow to the air conditioner. To limit the energy input to the generator thereby avoiding the "prevent cutoff" (to be discussed later), a system of flow bypass valves is provided, and they operate as follows. If the control temperature at T-8C[2] is between 210° F and 220° F, all flow passes through the air conditioner generator; if the inlet water temperature at T-8C increases to 220° F, MV-4 opens and 3.7 gpm (flow is initially set by regulating hand valve HV-14) is bypassed around the unit; if the temperature at T-4C rises to 230° F, MV-5 opens and allows an additional 1.8 gpm (all flow rates were set initially by regulating the appropriate hand valve in the flow loop) to bypass the air conditioner for a total bypass flow of 5.5 gpm. The temperature at T-4C will not exceed 250° F because of collector control

2. A "C" following instrumentation parameters indicates use for control only.

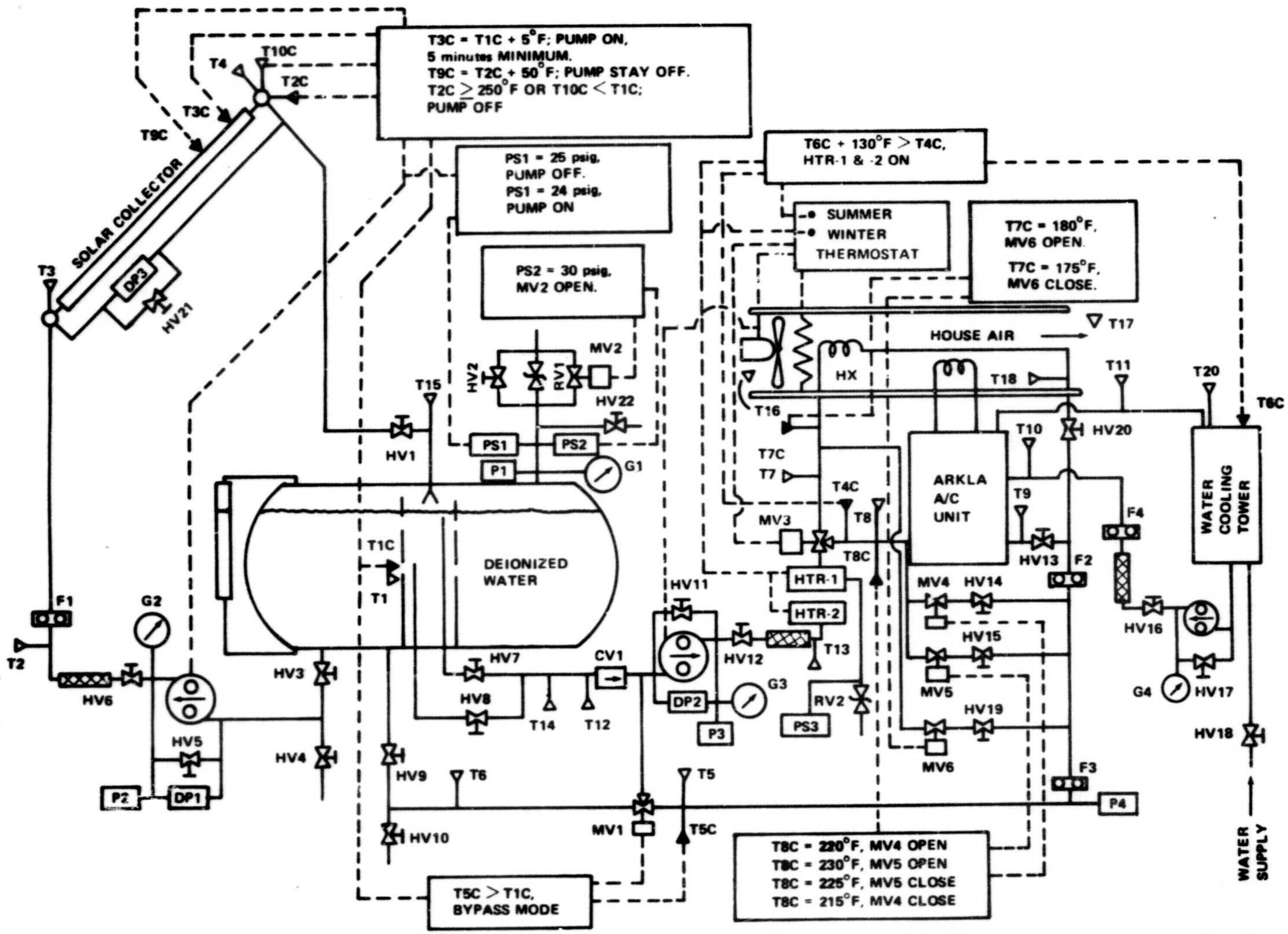


Figure II-9. Fluid system valving schematic.

logic cutoffs. Flow through the ARKLA unit generator is measured by flowmeter F-2 and total flow is measured by flowmeter F-3, the difference of which gives bypass flow. The hot fluid then passes through HV-9 into the thermal storage tank. If the temperature at T-8C falls to 225° F, MV-5 closes and reduces the bypass flow to 3.7 gpm. When the temperature at T-4C drops to 215° F, MV-4 closes and allows full flow to again be directed through the air conditioner generator and then through MV-1 back to the thermal storage tank.

3. Bypass Mode Flow. Bypass flow is triggered when the return temperature from the air conditioner measured at T-5C is greater than the temperature within the thermal storage tank as measured at T-1C; MV-3 directs 100 percent of air conditioner pump flow to the thermal storage tank bypass. Check valve CV-1 prevents the flow of water from the storage tank. In this mode of operation, all heat required to operate the air conditioner is supplied by electrical energy in the heaters (HTRS). A total of 18 kW is provided by 13.5-kW and 4.5-kW calrod units. Control of electrical heater HTRS is independent of the operational mode; i.e., it may be in operation either in the bypass or storage tank flow mode depending upon storage tank water temperature and outside wet bulb temperature. If the sum of cooling tower wet bulb temperature as measured by T-6C + 130° F is greater than the temperature at T-4C, heaters HTRS will be energized to supply heat. If the sum T-6C + 130° F is less than the pump outlet temperature as measured at T-4C, heaters HTRS will be de-energized. In the bypass mode, the cycling situation described above will continue until the temperature within the storage tank at T-1C reaches a value greater than T-5C, at which time MV-1 will position to provide 100-percent flow to the storage tank. When the air temperature in the dwelling decreases below the thermostat set point, the air circulation fan, AC/Htr water pump, and the cooling tower water pump and fan are simultaneously deactivated.

4. Heating Mode. In the event cool weather operation requires heating, manual selection of cooling on the wall-mounted thermostat causes the three-way heating/cooling valve (MV-3) to divert flow from hot water to the air conditioner to hot water flow to the winter heat exchanger. All subsequent operations are automatic with the logic system providing a nominal 3.5-gpm bypass (MV-6 open) around this heat exchanger should water temperatures rise above 180° F. In the event water temperatures from the tank are too low to provide sufficient heating, three electrical strip heaters located in the gas flow duct are activated. These heaters are cycled on in three stages at 2-deg increments below the thermostat set point to give a total of 20-kW heating capability. Since this loop was not activated during these tests, no discussion of tests results is given. However, in the future, tests are planned to verify this system.

G. Trailer Complex

The trailer complex, which makes up the "dwelling" to be cooled and heated, is constructed of three surplus office-type house trailers, two 10 ft by 58 ft and one 12 ft by 30 ft, secured together with interconnecting doors to form a 1520 ft^2 floor plan (Fig. II-10). This complex is situated with its long dimension parallel to an east-west line such that one face of the roof faces due south. Since trailer construction does not provide sufficient strength to support a roof structure of even minimum structural requirements, a free standing roof was constructed over the trailers to support the solar collector subsystem and associated plumbing. The roof, which is supported on fourteen 6 in. diameter steel posts set in concrete, has a 45-deg slope and utilizes trussed rafter construction with rafters placed on 24-in. centers.

Although the roof provides a shading effect, no special thermal protection has been intentionally provided to the trailers. Metal skirts are located around the trailer complex periphery at its base; these inhibit air flow under the trailer but were provided for aesthetic reasons. The outer walls and north roof are covered with commercially available white latex paint. The air conditioning ducts are insulated with common 1.5 in. thick fiberglass insulation and are routed under the trailers to the various rooms.

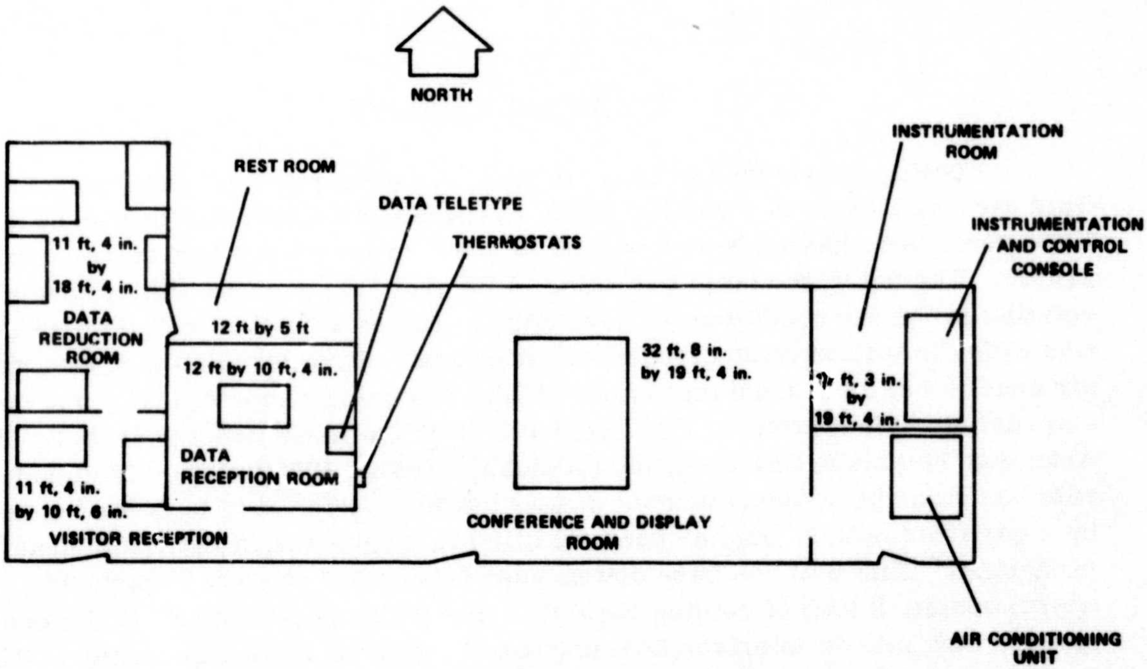


Figure II-10. Solar house floor plan.

H. Energy Storage Tank

The energy storage subsystem is shown in Figure II-11. The basic component is a 4700-gal aluminum storage tank that contains 3550 gal of water. The tank is housed in a wooden "house-like" structure for weather protection. Common household insulation has been installed to achieve a minimum thickness of 12 in. of insulation on all sides. The tank, which is a space program surplus item, has 0.5 in. thick walls and is fabricated of 5154 aluminum.

The tank has been modified internally in an attempt to provide the hottest water to the AC/Htr loop while providing the coldest fluid to the collector inlet. To achieve this an 8 in. diameter pipe was welded to the bottom of the tank (Fig. II-12). The hot water from the collector is dumped into the top of the standpipe, while the water supplied to the AC/Htr loop is also taken from the standpipe just below the liquid level. The cold water from the AC/Htr loop is dumped back into the bottom of the tank. The collector supply is taken from the bottom of the tank. Flow to and from the standpipe into the tank proper is through four 2 in. diameter holes equally spaced at each of two levels in the standpipe.

Initial filling of the tank caused the water level to be about 60 in. from the tank bottom. When the collector is not running, water drains from the collector and its manifolds. The water level of the collector system is 4 in. below the inlet manifold.

I. Air Conditioner

Cooling is provided to the trailers by an absorption air conditioner. This air conditioner is a commerically available unit which was driven by a gas fired generator, having been modified to incorporate a hot water driven generator. The hot water boils the water vapor from the aqueous lithium bromide solution in the air conditioner. The boiling creates a "coffee pot" type percolation which in turn creates circulation in the unit. This percolation allows the air conditioner fluid medium to flow without requiring a mechanical pump and external electrical power. This particular unit was sold commercially by the Arkansas Louisiana Gas Company (ARKLA) through 1967 but its commercial sale has since been discontinued. It was initially designed to be heated directly by a gas fired boiler, but has been modified to incorporate a hot water heat exchanger. This unit has been downgraded from a 4.1 ton unit to provide approximately 3 tons of cooling capacity. Hot water is pumped from the energy storage tank into an interface heat exchanger referred to as a generator. The incoming water temperature may be raised using auxiliary heaters in the event the water tank temperature is inadequate.

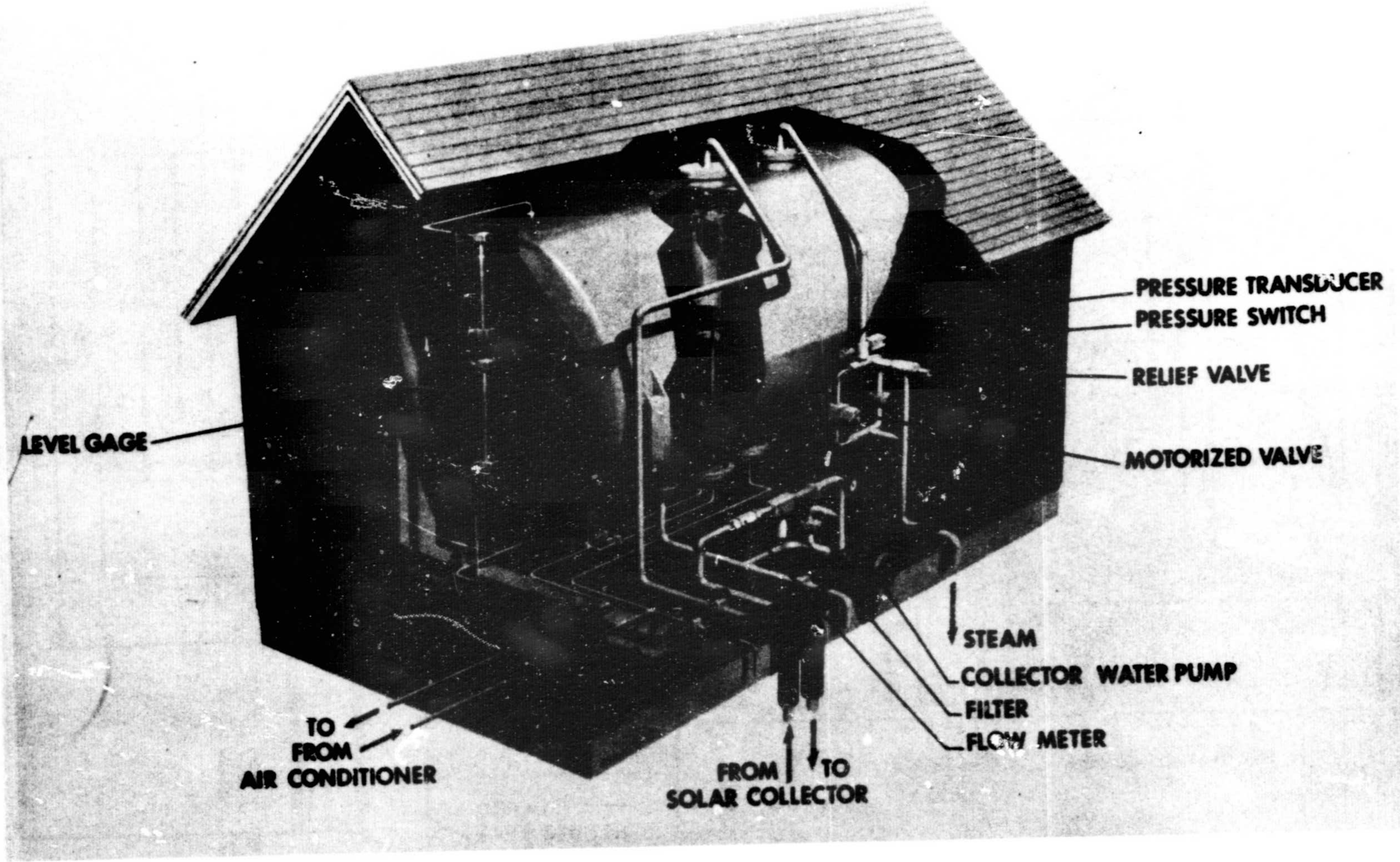


Figure II-11. Energy storage tank arrangement.

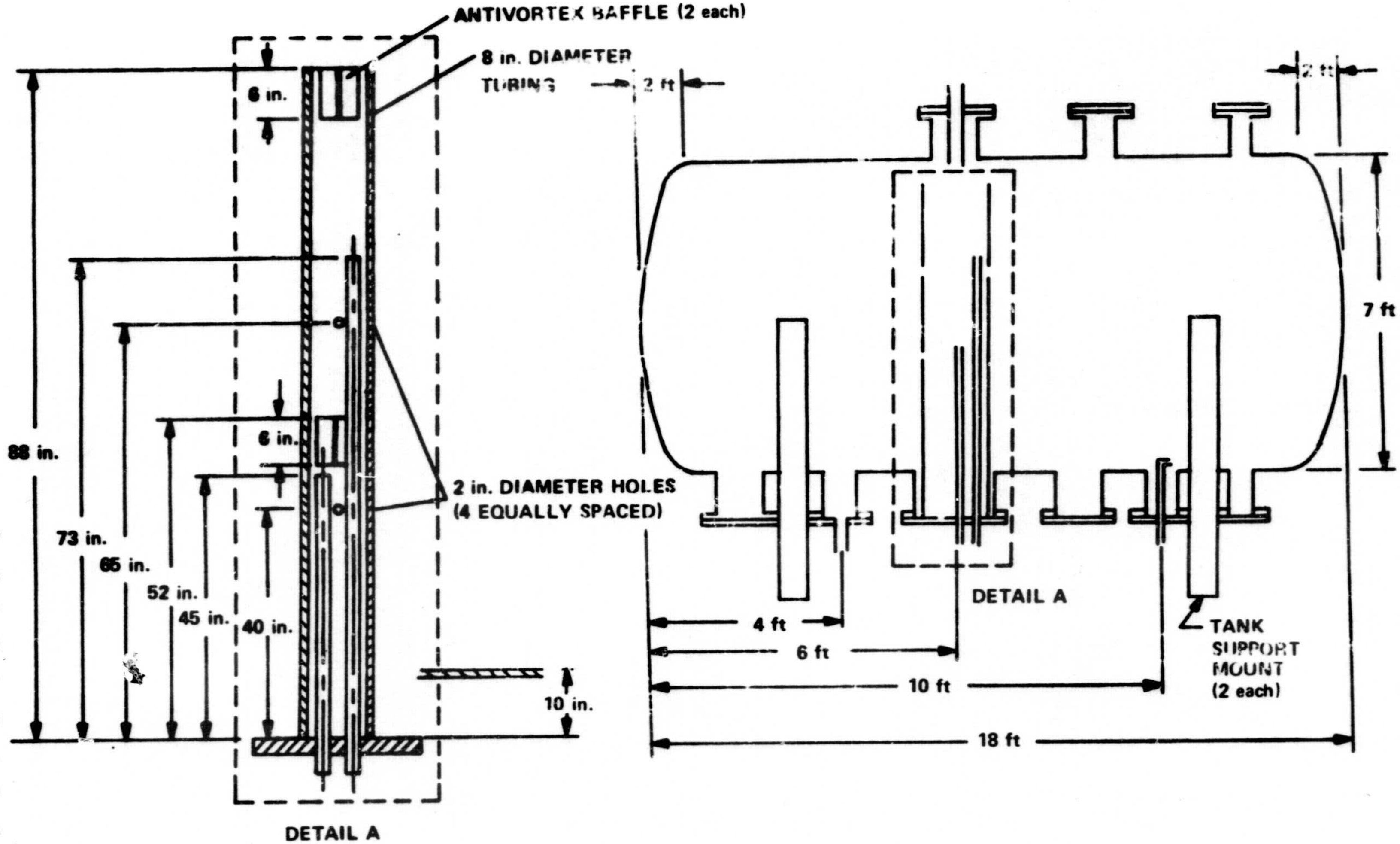


Figure II-12. Energy storage tank details.

The lithium bromide/water cycle (Fig. II-13) operates under a reduced pressure, approximately 58 mm Hg at the generator to 8 mm Hg in the evaporator (cooling coil). After the water vapor leaves the mixture in the generator it passes through the condenser where it is cooled to near ambient temperature and heat is rejected to the cooling tower water loop. Upon leaving the condenser the vapor passes through the expansion valve where it is reduced in pressure and temperature. After passing the expansion valve, the refrigeration effect is obtained in the evaporator by water boiling at the low pressure which normally provides an evaporator surface temperature of from 36 to 50° F. Heat rejection to the evaporator is accomplished by a fan blowing air across the coils at approximately 1200 cfm. The cooling tower provides a heat sink for the air conditioner to cool the water vapor in the condenser and in the absorber (immediately downstream of the evaporator) where the water vapor is reduced to the liquid state. In this state it has a strong affinity for the lithium bromide and consequently recombines. Special protection circuitry is provided by the manufacturer to assure that the water vapor is not overchilled thereby allowing unwanted ice formation. An additional protection system is provided to avoid emptying a liquid trap between the generator and absorber. These protection systems will be referred to as the "low temperature cutoff" and the "prevent cutoff," respectively. In addition to the protection circuits a low temperature water bypass valve is provided to avoid allowing unacceptable cool water to flow through the condenser/absorber combination. This system is designed to bypass approximately one-half of the water from the cooling tower at inlet water temperatures below 75° F.

J. Data Acquisition

The data acquisition system may be divided into two main categories, real time and delayed data acquisition. The first category may be further subdivided into the real time Astrodata system, the Olivetti real time system, and strip charts. The Astrodata system outputs data via a central computer that has been processed to yield information in engineering units on two teletype printers, one of which is located in the solar house. Two digital displays are also available in the solar house which have access to the Astrodata system. Single and dual strip charts are available in the instrumentation room of the solar house.

Data flowing to the solar house teletype is accessed electronically by an Olivetti computer also located in the house. This computer is used to provide calculations on a near real time basis for six parameters:

1. Energy collected.

2. Energy consumed by the air conditioners.

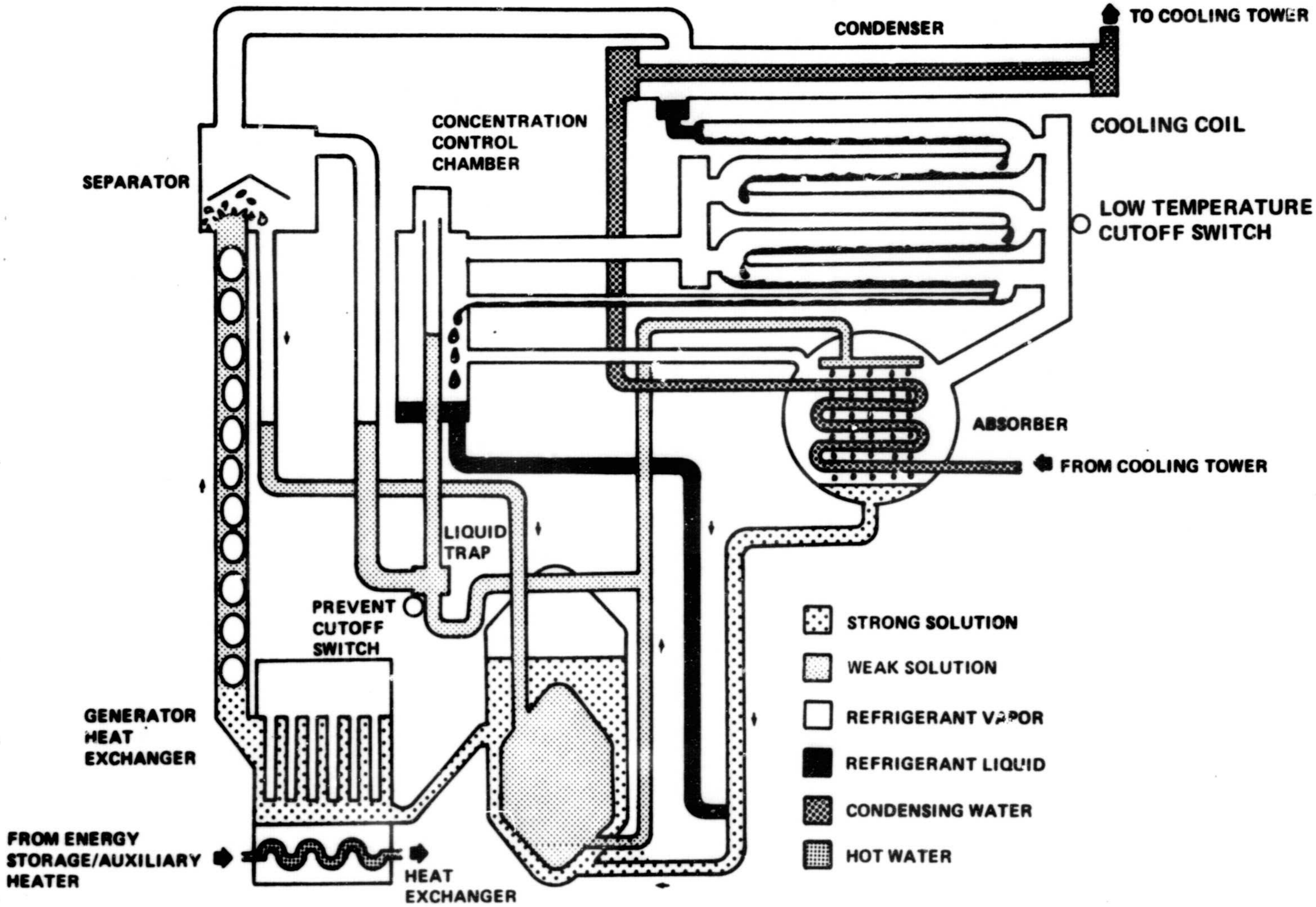


Figure II-13. Lithium bromide absorption air conditioning system.

3. Total incident energy.

4. Energy incident while collecting.

5. Energy available in the water tank.

6. Total collector efficiency.

Values for these parameters are automatically printed on a paper tape. The first three parameters are also automatically plotted by an extension of the Olivetti.

Since the Astrodata system cannot print out as much data as it has the capability of recording on magnetic tape, some data are processed only by the MSFC Data Systems Laboratory directly from the tape. In addition to these raw data reductions, the real time information printed on the teletype is also reduced by the Data Systems Laboratory. Thirty other channels of information in the Astrodata system, which may be accessed in real time by a special operation, are also reduced by the Data Systems Laboratory. Reduction of these data consists of plotting and tabulating both raw data and calculated parameters versus time. Some 50 parameters used in system performance evaluation are calculated and plotted using the raw data.

Because of Astrodata system limitations and Olivetti data input requirements, only 63 measurements of the total of 110 are automatically printed in real time. Thirty-three of the more important measurements are printed every 250 sec with the remaining 30 printed every 500 sec. The Astrodata system has a nonautomated printout capability for an additional 30 measurements at 50-sec increments. However, these measurements are printed only once per day to avoid excessive interference with the Olivetti. Initially, this left only 17 measurements to be reduced solely by the Data Systems Laboratory. However, 11 measurements giving air conditioner fluid loop temperatures have been added since testing began, increasing the number of measurements that are not accessible in real time to 27 and raising the total number of measurements to 120. Plotted values of all these parameters are combined to form daily solar house data books. Figure II-14 depicts the data flow scheme, and Table II-1 gives a summary of data acquisition.

K. Instrumentation

All temperature measurements are made using copper-constantan thermocouples. All thermocouples were compared to a 150° F constant temperature reference junction. The 45-deg-mounted pyranometer and a similar

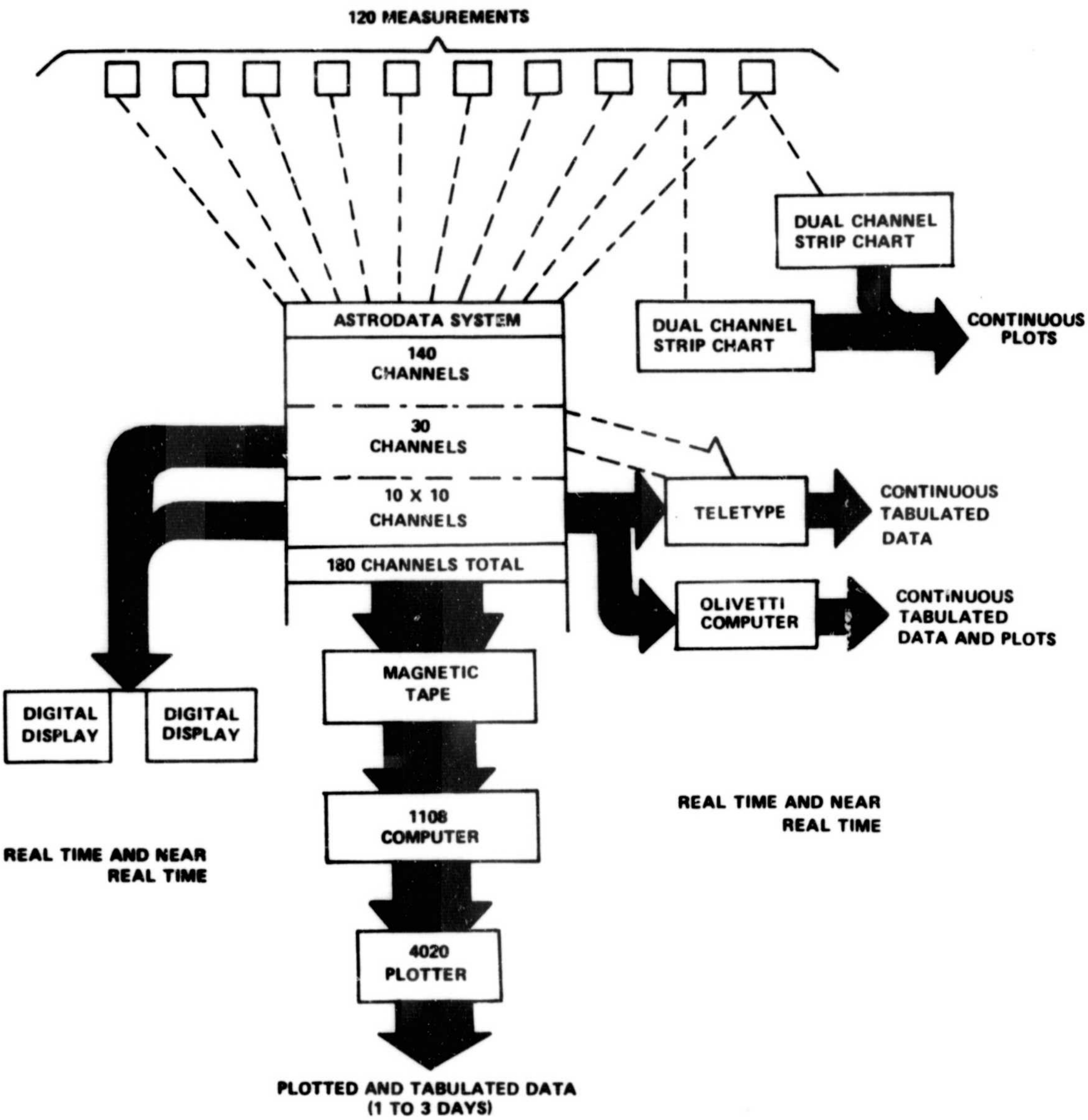


Figure II-14. Data flow chart.

sensor mounted beneath the Tedlar were manufactured by the Weather Measure Corp. All liquid flowmeters are Potter Co. turbine type flowmeters. The relative humidity sensors were manufactured by the Phys-Chemical Corp. Pressure transducers, differential and absolute, are MD Electronic Co. strain gage type sensors. All power measurements were made with General Electric watt-meters.

TABLE II-1. DATA ACQUISITION SYSTEM SUMMARY

A. Real Time and Near Real Time Data

1. Astro-Computerized Data

   a. 63 Measurements Automatically Printing Continuously

   b. 30 measurements Printed as Required (Normally Once per Day)

   c. Two Digital Displays

2. Olivetti Computer Calculations

   a. Three Plotted Parameters (During Collection Periods)

   b. Six Tabulated Values (At all Times of the Day when the Astrodata System is Functioning)

3. Strip Charts

   a. Four Measurements on Two Separate Strip Charts

B. Delayed Data (1 to 3 Days after Acquisition)

1. Raw Data from Astrodata System

   a. Plotted

   b. Tabulated

2. Calculated Data

   a. Plotted

   b. Tabulated

A check was run during these tests to assess the accuracy of thermocouples. From this check, it appears that most temperatures are accurate to ±0.5° F.

Figure II-15 shows a schematic of instrumentation in the fluid and gas loops with power measurements also shown. Figure II-16 depicts instrumentation on the collector and Figure II-17 shows instrumentation within the energy storage tank.

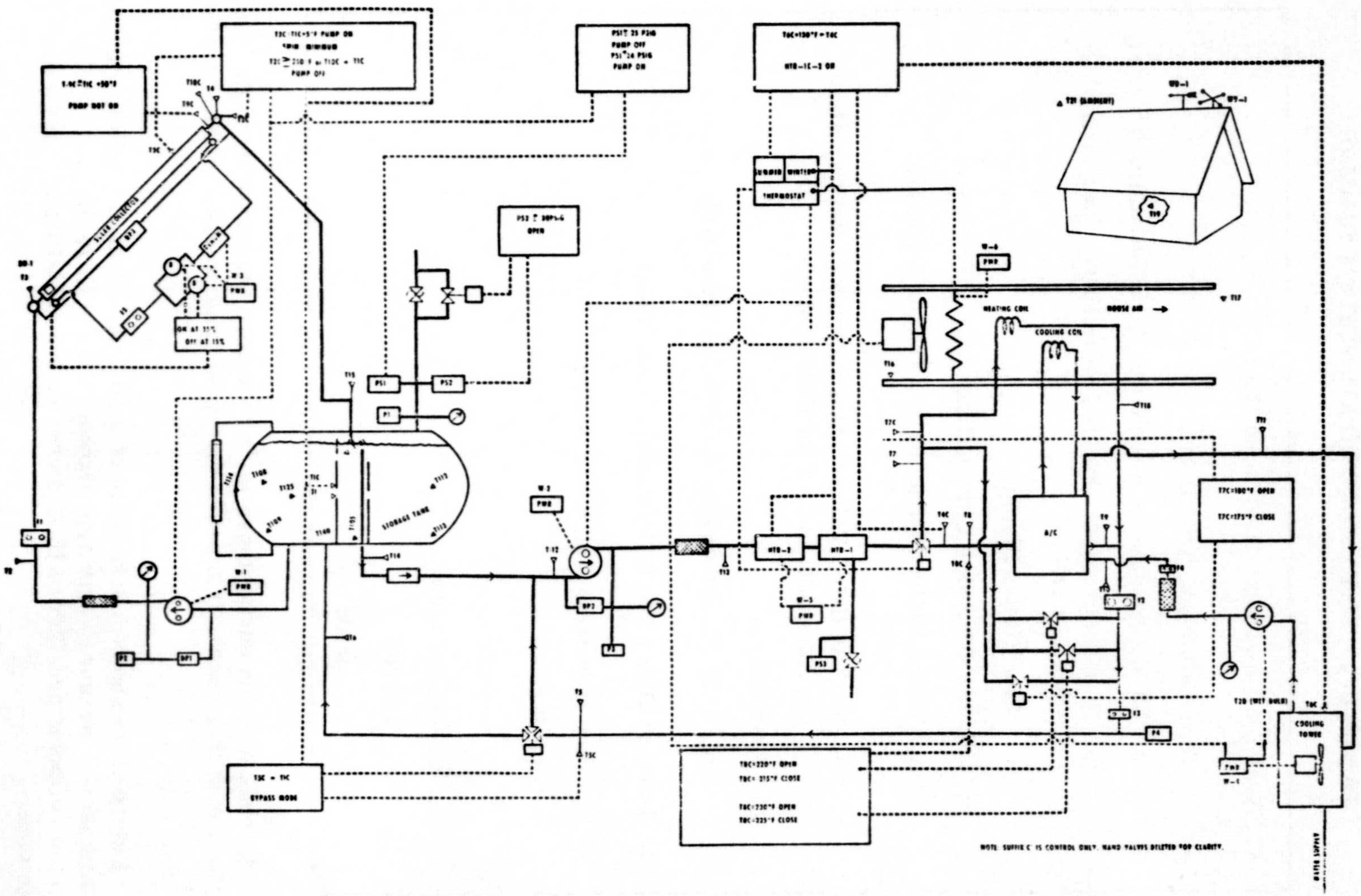


Figure II-15. Solar house fluid loop instrumentation and control schematic.

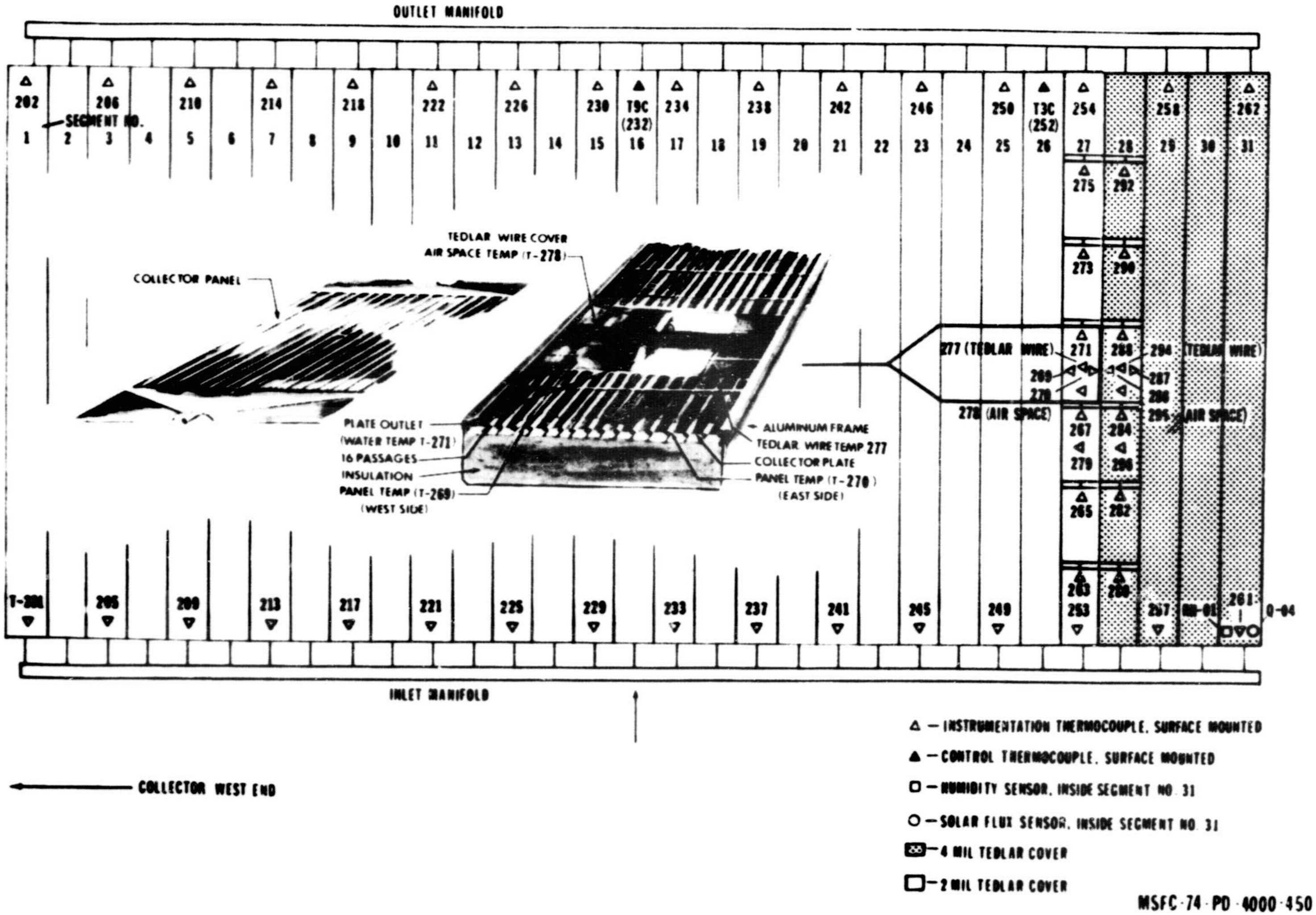


Figure II-16. Identification and location of instrumentation on solar collector.

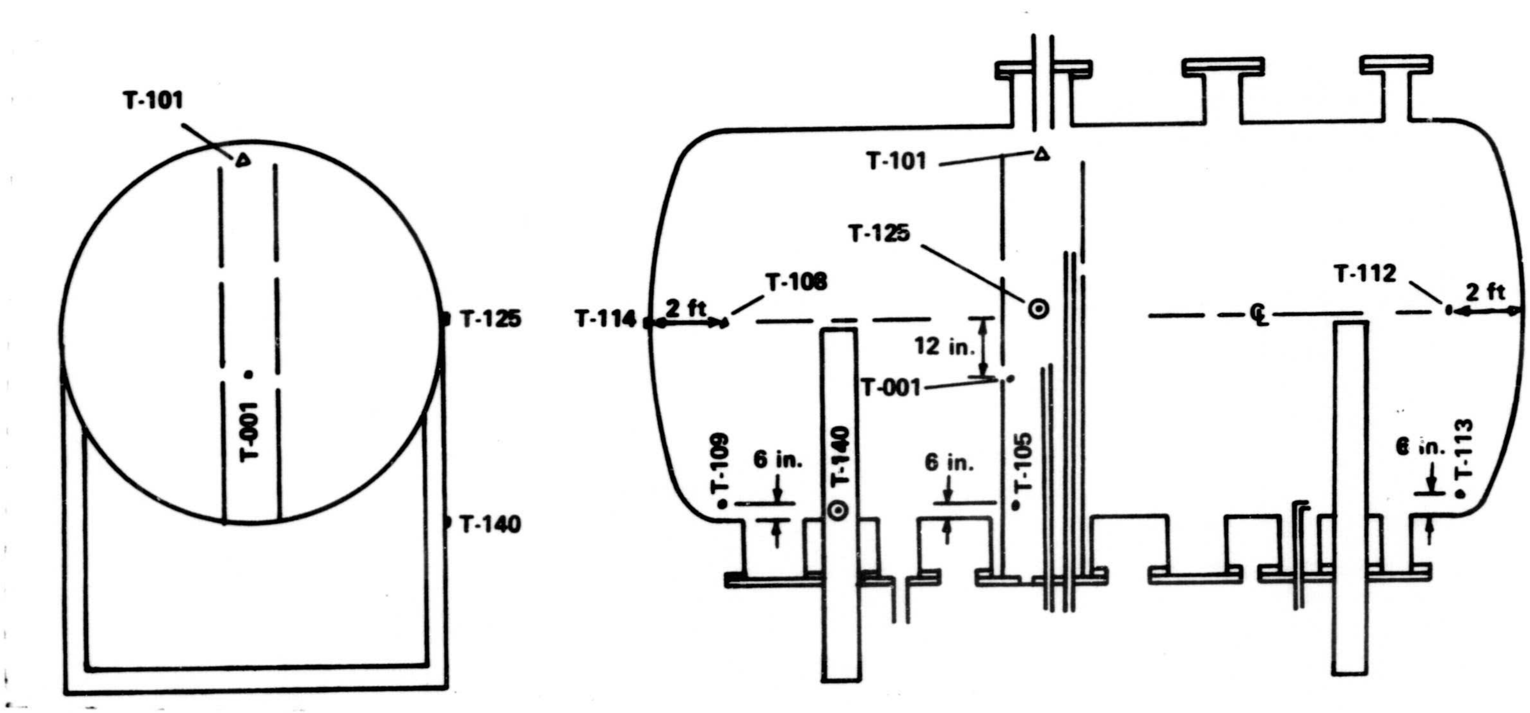


Figure II-17. Energy storage tank instrumentation.

III. TEST DATA AND EVALUATION

A. General

The philosophy of this test program was to construct a solar heated and cooled facility using the best designs that could be accomplished with readily available, current state-of-the-art equipment. This goal was accomplished within a tight schedule. As a result, it was impossible to realize a high degree of system optimization or to achieve complete simulation of typical home application hardware.

The object of the program was to gain practical insight into continuous operation that would be applicable to commercial and residential facilities of this type. The facility was operated over a broad spectrum of weather conditions and random seasonal variations imposed by the north Alabama climatic zone.

This report covers only the 3 months from initial test activation of the facility, in late May, to the first of September. During this period of testing the system configuration was changed several times to exploit information obtained from the tests and to correct system problems. Most changes occurring in this phase of testing affected the collector loop and air conditioner/heater loop logic systems. Minor collector modifications and repairs were also performed during this period.

Because of the significant variation in day-to-day results, most performance assessments are made based on average values. In the interest of brevity, all parameter variations, occurrences, and test data are not presented. The bulk of the data contained in this section addresses problems that apply in general to any system of this type, with emphasis placed on assessing subsystem and overall system performance.

B. Collection Subsystem

During initial testing water was noted to have leaked under the Tedlar cover. This rain water leaked into the collector pans by flowing through the Tedlar cover-to-frame caulking joint, permeating part of the insulation protection system. After the water was drained, the caulking was found to be a type that had been substituted during fabrication and would not bond to Tedlar. The

joints were then recaulked with the proper caulking compound. After this repair was completed the collector subsystem was operated in the rain after which previously wet insulation was rechecked and found to be dry. No further difficulties with rain water leakage have been experienced.

The collector segments were mounted on the roof in March; they were later removed for 2 weeks for minor repairs and replaced. During this initial 8 to 12 week period after installation, noticeable discoloration or "clouding" of the Tedlar occurred. Figure III-1 shows a sample of Tedlar which had been exposed from December 1973 to June 1974 in a prototype test segment under similar test conditions. For comparison, a clear, unused sample is also shown on the right side of Figure III-1. From this photograph, the transmissivity degradation is obvious from the white appearance of the degraded sample. The degradation was determined by chemical analysis to have resulted from the depositing on the tedlar of condensable offgassing products from a binder used in the fiberglass insulation battens. Tests of two samples taken from the prototype segment indicated transmittance values of 82.6 percent and 73.4 percent. These values may be compared to the initial undegraded transmittance of 94 percent. Alcohol cleaning of the samples restored the original transmittance. In the future, this problem should be avoided by either using fiberglass qualified at higher temperatures than the common household material used or by driving off the offgassing products in an oven prior to use. Heating the fiberglass to 800°F for five minutes or to 500°F for 30 minutes will remove the undesirable products.

A close scrutiny of the cover reveals darkened areas around the wire mesh. These darker areas are the epoxy glue used to attach the mesh to the Tedlar. This glue, which is relatively transparent on initial application, darkens after sun exposure. This darkening has the unwanted effect of obscuring more collector surface than the simple projected area of the wire. Observations indicate that up to 15 percent of some segments are shaded by the wire/glue combination.

In an effort to determine the performance of the collector subsystem, the collector pump was twice run at night. During both these tests, the energy loss rate from the collector stabilized at 125 000 Btu/hour. Using this value, the loss flux rate was calculated to be 102.6 Btu/hour-ft^2, which is near the predicted value.

Collector performance is very difficult to accurately assess. This is primarily because it is a function of a number of variables which vary with time. Typically, for a given collector geometry, the system performance is

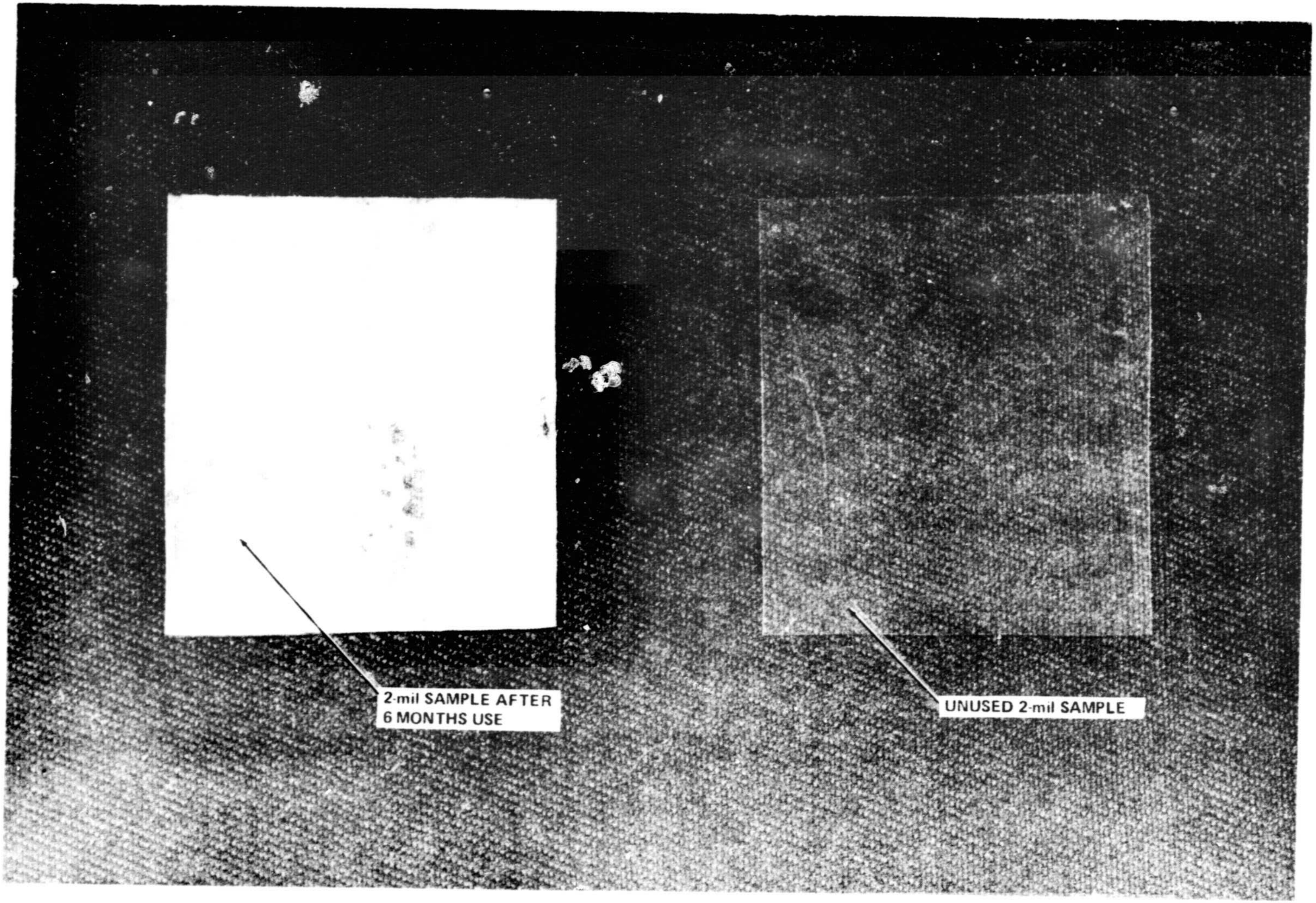


Figure III-1. Contamination of Tedlar resulting from outgassing.

a function of the average surface temperature, the incident flux, and the ambient conditions (temperature and wind velocity). Figure III-2 illustrates the typical effect of these parameters, excluding wind velocity. Variations in incident flux not only depend upon whether the weather is inclement or clear but also upon the degree of cloud cover. Figure III-3 shows typical examples of cloudy, partly cloudy, and clear days. As seen in this figure, the incident flux varies with time of day.

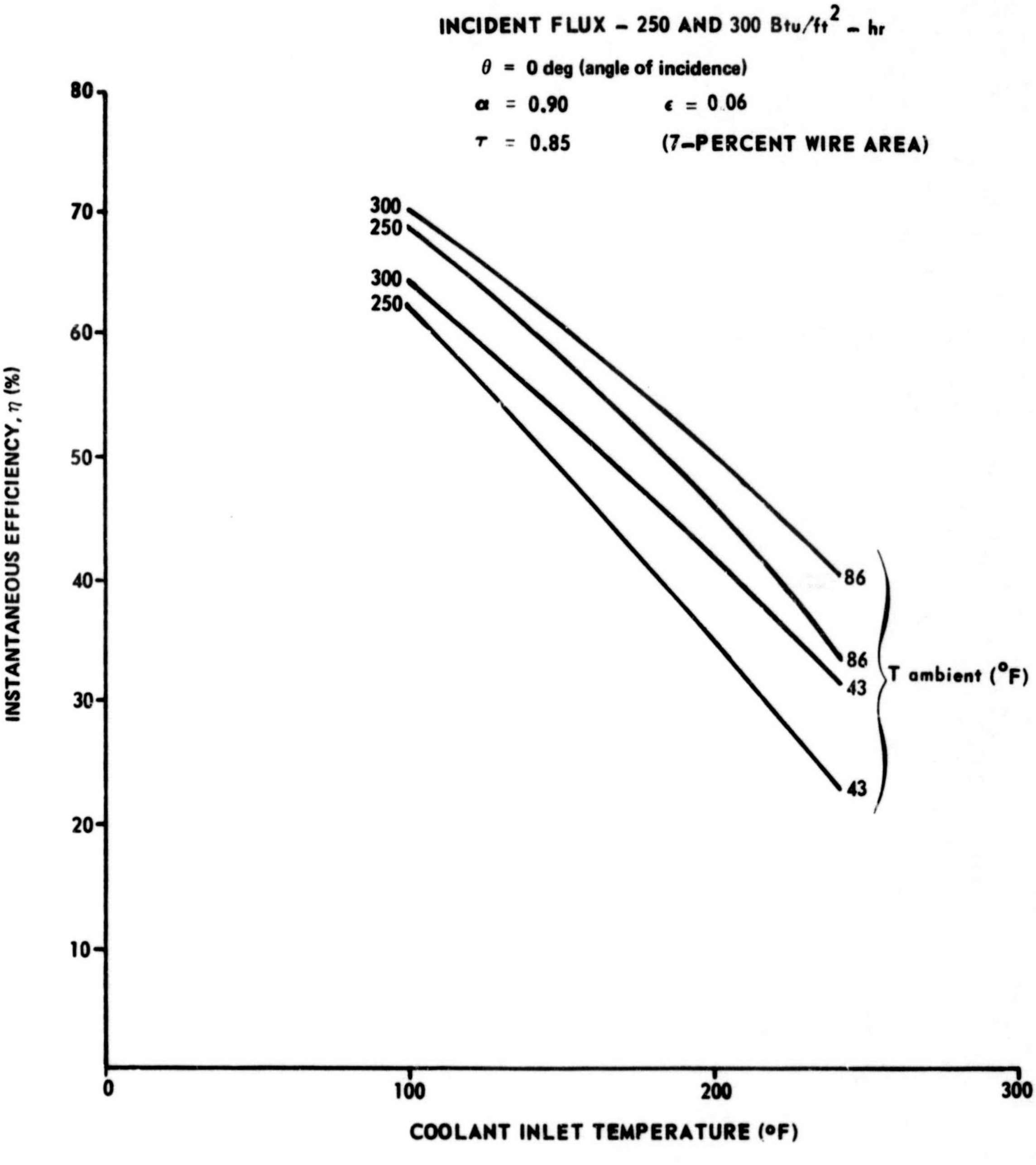


Figure III-2. Instantaneous collector efficiency.

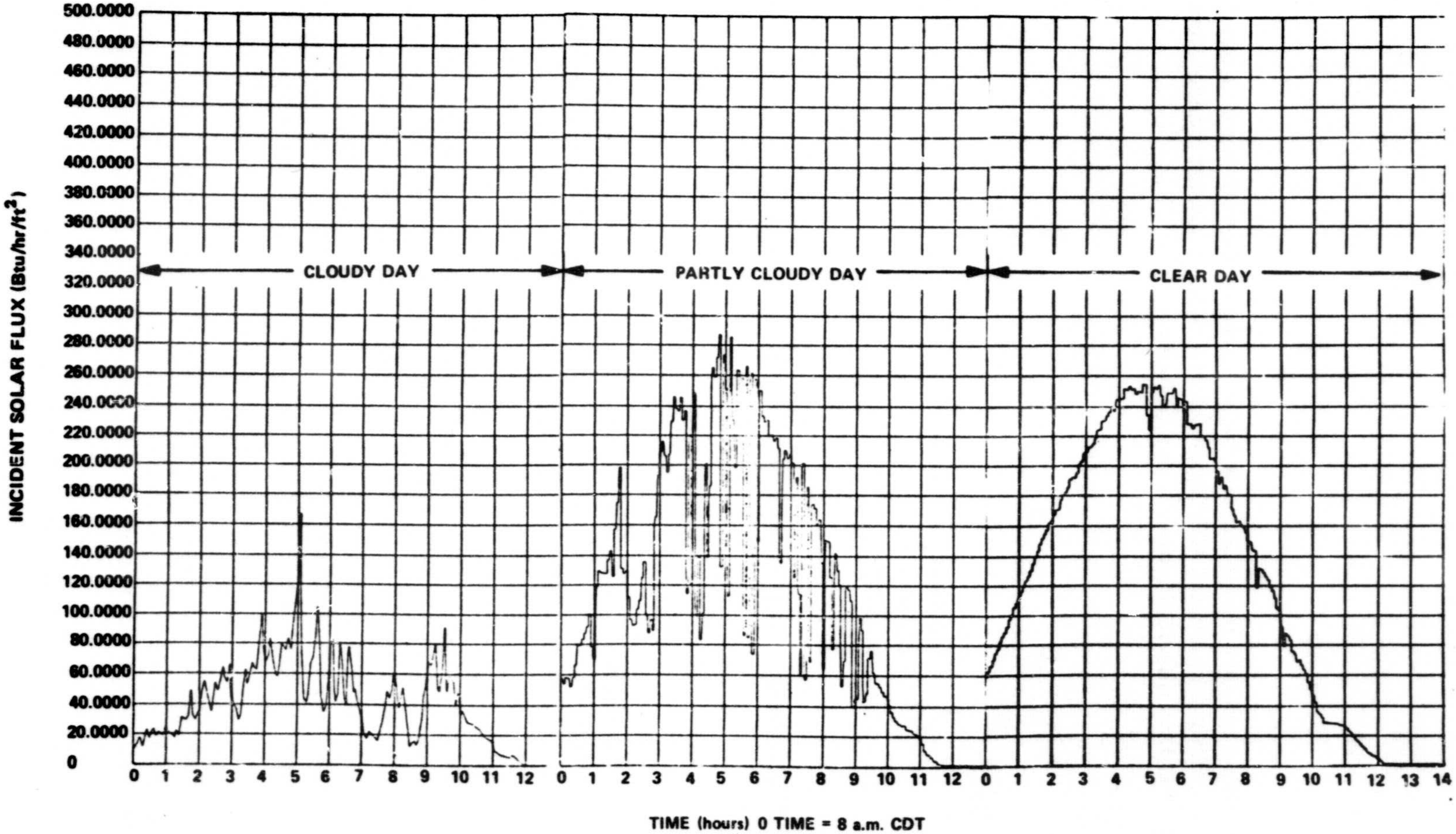


Figure III-3. Incident solar flux for various weather conditions versus time.

Defining the collector efficiency, η, based on instantaneous rates by

$$\eta = \frac{\dot{Q}_{\text{collected}}}{\dot{Q}_{\text{incident}}} ,$$

it is obvious that this instantaneous value varies also with time of day (Fig. III-4). A more meaningful efficiency from a system performance viewpoint is the integrated efficiency over a day defined by

$$\eta_T = \frac{\int_{\text{day}} \dot{Q}_{\text{collected}} \, dt}{\int_{\text{day}} \dot{Q}_{\substack{\text{incident} \\ \text{while} \\ \text{collecting}}} \, dt} .$$

Figure III-5 provides daily integrated efficiencies, η_T.

C. Trailer Complex

When making relative comparisons, the energy input to the trailer is extremely important. In determining the comparative size of this system in relation to a typical residential dwelling a number of contradicting factors must be considered. Some factors indicate the cooling load of the trailer complex is higher than an equivalent floor plan dwelling in this locale, and others indicate that this load is less. The shading provided by the collector offers thermal protection from direct sunlight from which a typical trailer or conventional dwelling would not benefit. However, the metal sides, thinner walls, unusually high waste heat levels, and high activity levels within the trailer induce larger energy inputs than a typical residential dwelling of this size would experience. The waste heat generated within the dwelling is excessive for a 1500-ft^2 dwelling.

During the period covered by this report, the high activity level within the trailer complex resulted in numerous openings and closings of the two access doors. A 2-week survey of the frequency of entries indicates an average

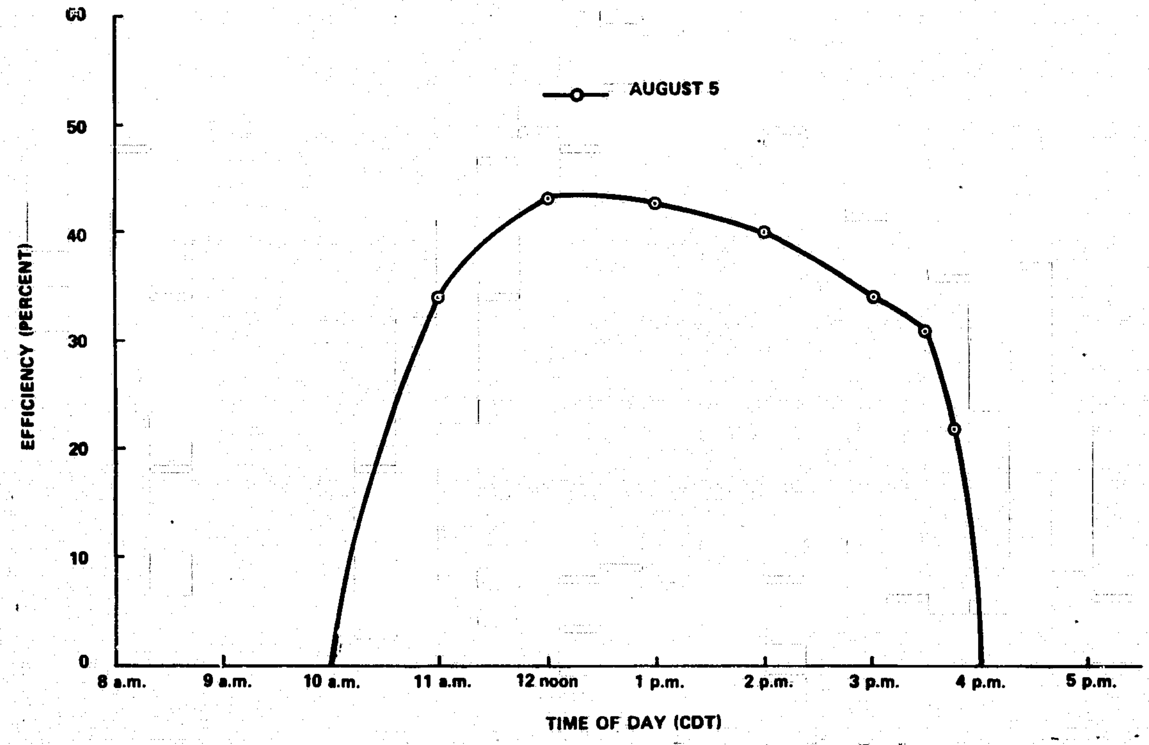


Figure III-4. Collector efficiency versus time of day.

of 73 entries and exits per day by an average of 28 persons. This high incidence of entries and exits is easily explained, since the complex was used as a work area by test and analysis groups and as a conference area, and was open to large and small tour groups. University cooperative students, who assisted in data reduction and performed facility monitoring tasks, inhabited the facility 24 hours per day. An estimate of 120 man-hours of utilization per day of the trailer is reasonable. Added to this, instrumentation and control equipment housed in the trailers averaging approximately 700 W was operative 24 hours per day. A summary of the lighting and miscellaneous equipment loads shows that a maximum load of 3710 W is possible. Table III-1 summarizes these values.

Integrating the total cooling provided by the air conditioner for a number of representative days and plotting against the average difference in the ambient temperature and the thermostat set point gives the results presented in Figure III-6. The negative values on the abscissa result from using the average ambient temperature for the entire 24-hour day. The fact that the air

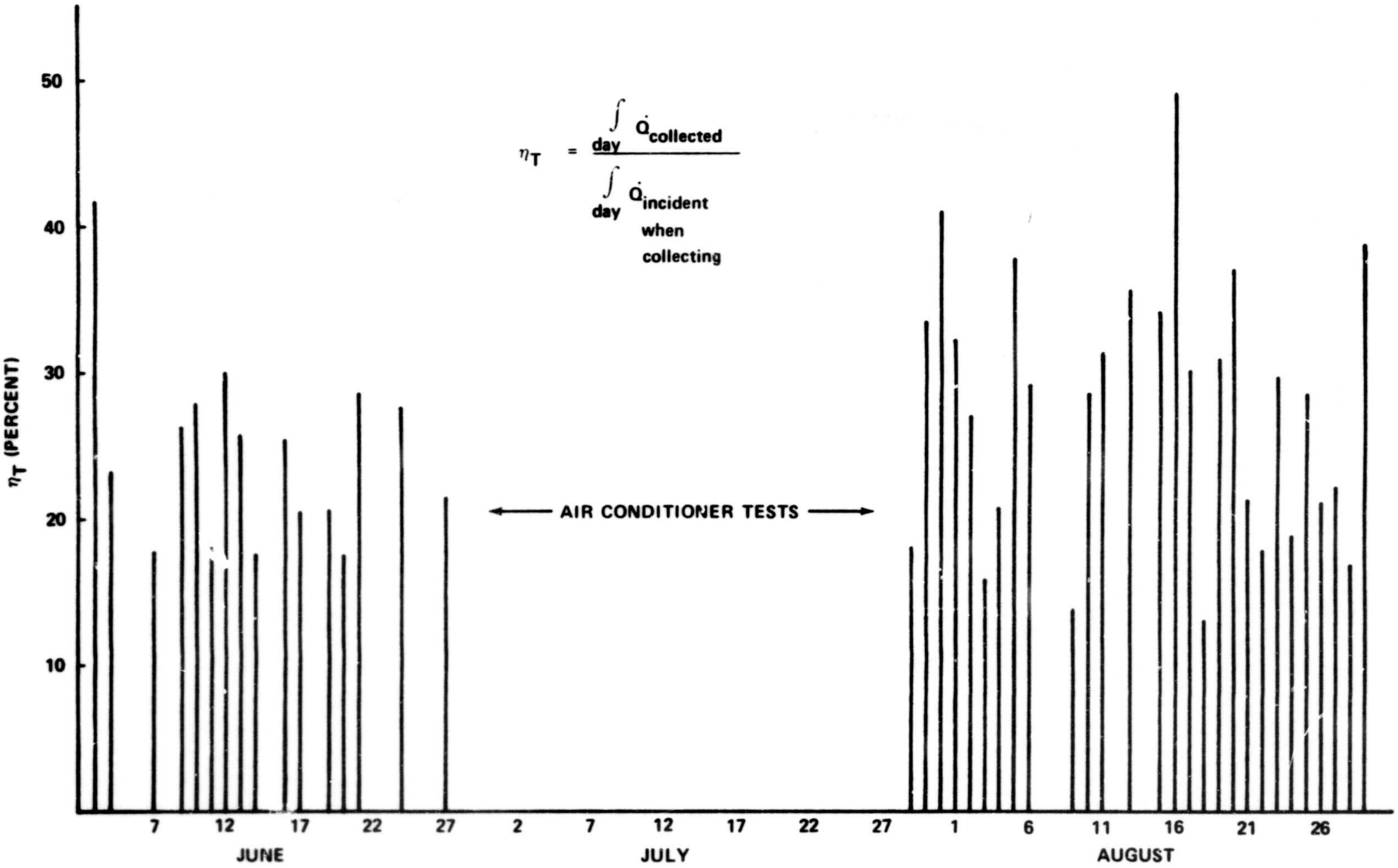


Figure III-5. Integrated daily collector efficiency.

TABLE III-1. WASTE HEAT SUMMARY

Item	Maximum Wattage	Estimated Percent of Usage	Average Wattage
Lighting	2190	80	1752
Miscellaneous Equipment	320	100	320
Air Conditioner Blower	500	40	200
Instrumentation and Controls	700	90	630
Totals	3710		2902

conditioner came on during cool nights is probably a result of the high internal loads discussed earlier and the baseline of operation. This baseline armed the thermostat 24 hours per day with all windows and doors closed regardless of the outside temperature.

D. Energy Storage Tank

Temperature stratification was observable in the energy storage tank when the air conditioner was running without the collector. Stratification is a result of the colder fluid flowing from the air conditioner outlet into the bottom of the tank and not mixing with the warmer fluid in the upper tank. Stratification was evident at all flow rates but was more pronounced at lower flow rates. Using the lowest temperature, T-105, the temperature decrease after 1 hour of air conditioner on-time without collector operation and at each of four air conditioner flow rates is given in Figure III-7. Since the energy being removed by the air conditioner was lower for lower flow rates, different temperature gradients were to be expected; consequently, the actual temperature drop was corrected for each case by subtracting the temperature drop that would have been caused by the energy loss if the tank acted as a uniform mass, $\Delta T_{corrected} = \Delta T_{actual} - \dot{Q}_{gen}/\dot{m}c_p$.

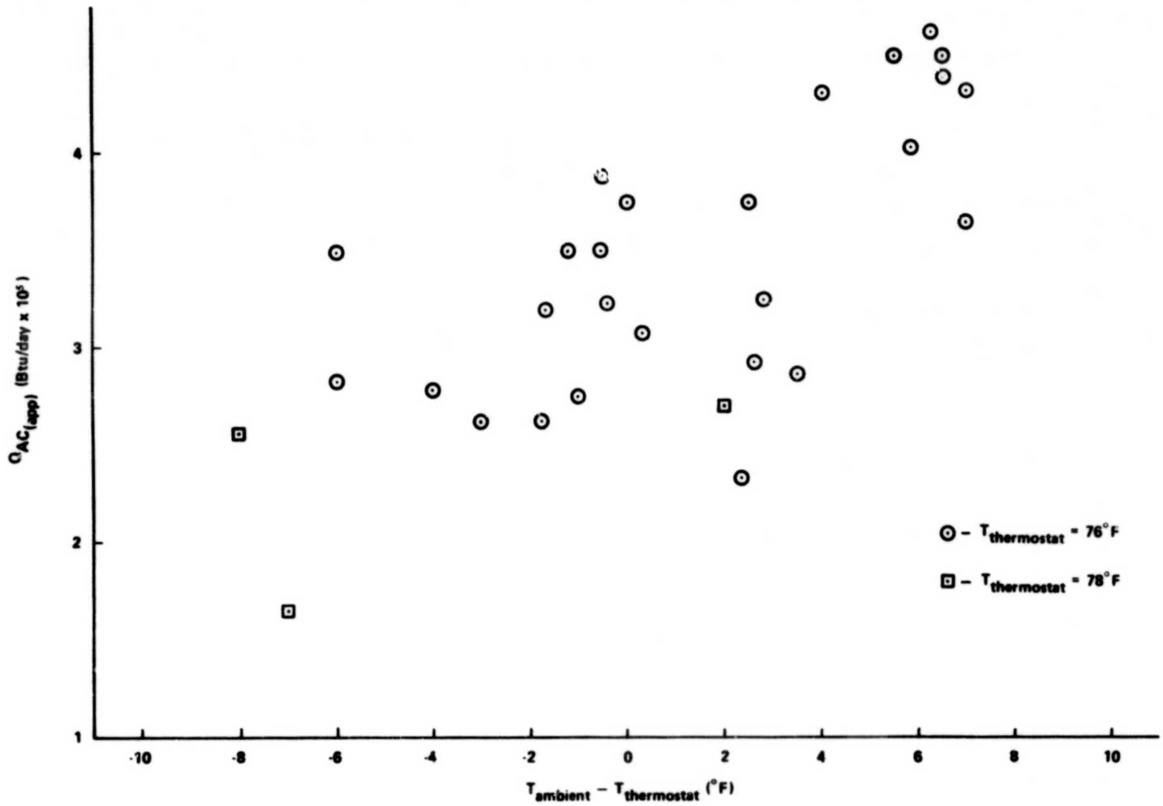


Figure III-6. Trailer cooling load.

From these data it is obvious that stratification is a desirable phenomenon for this plumbing configuration because it causes the warmest fluid to be supplied to the air conditioner and the coolest to be available at the collector inlet. As a result, operating at lower air conditioner flow rates has the added benefit of causing colder fluid to be supplied to the collector.

Future studies are planned to determine the advisability of adding a direct flow path between the air conditioner outlet and the collector inlet. This would allow the colder air conditioner return fluid to enter the collector when both are operating. However, the advantage of such a modification must be weighed against the cost of added hardware.

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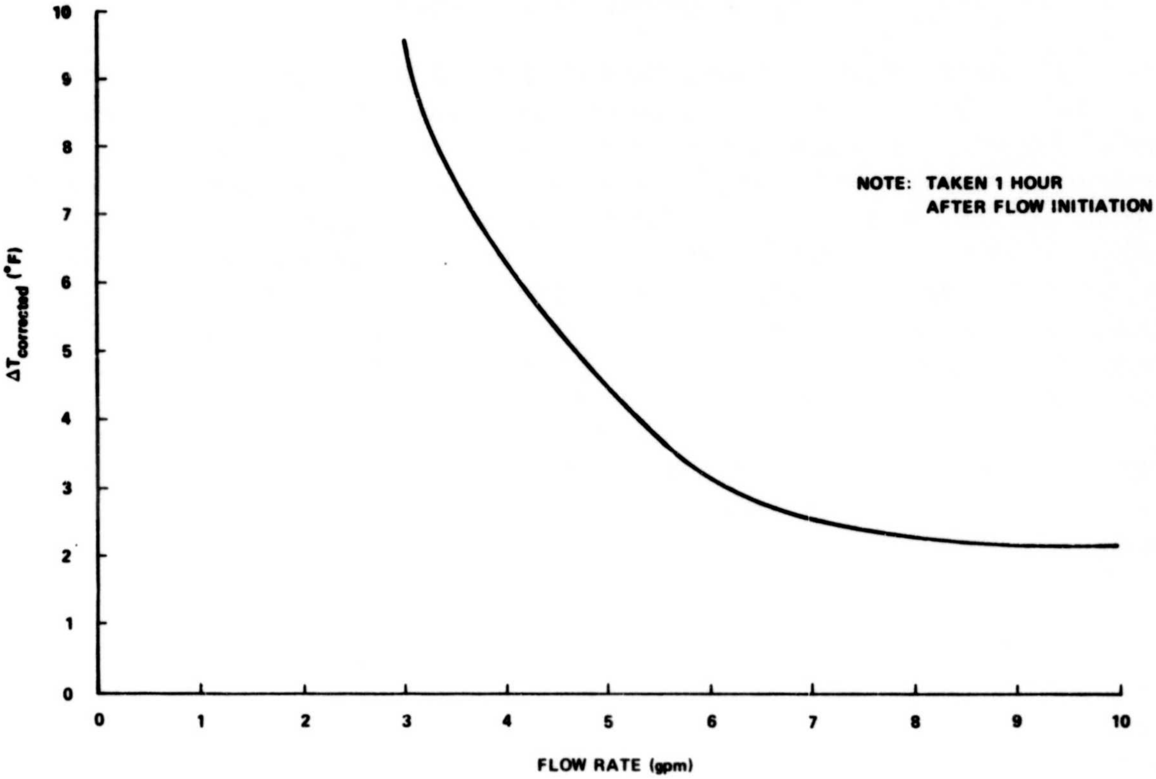

Figure III-7. Corrected stratification temperature differential versus air conditioner flow rate.

E. Heat Losses

In a system this size, large heat losses may be encountered. Even in the case where systems are well insulated, heat shorts inherent in structural support and large surface area to volume ratios are significant. The exact value of heat losses in lines and components is difficult to obtain directly because the losses are reflected by only very small fluid temperature changes. As a result, the total heat loss for this system was assessed by using a total energy balance over relatively long periods of time. A typical loss rate of 180 000 Btu/day was observed.

By using energy storage tank temperatures during a number of dormant nighttime periods where tank energy loss is relatively easy to assess, the storage tank heat loss can be determined. This loss was from 40 000 to 65 000 Btu/day. Pretest calculations had indicated a total loss rate of 160 000 Btu/day and a tank loss rate of 45 000 Btu/day, both of which are in very close agreement with the test data.

F. Modified Logic System

Evaluation of data accumulated during the early phases of testing indicated that modifications to the control system should result in improved system efficiency. It was apparent that the air conditioner was consuming excessively high levels of energy especially at higher generator inlet temperatures. Testing was terminated and studies of the absorption system thermodynamics indicated the air conditioner coefficient of performance (COP) would increase at lower generator temperatures and flow rates. However, the key to operation of the unit at these reduced levels was to assure percolation. Within the envelope of existing hardware a lower inlet temperature and/or a bypass flow rate keyed to the inlet temperature were the only feasible options. However, since very little data were available from the manufacturer, the exact effects of changing the flow rate through the air conditioner and lowering the inlet temperature were not known. As a result a series of tests was conducted to assess these effects.

The range of generator water inlet temperatures tested was from 181° F to 223° F. The flow rate through the generator was set at 10 gpm, 7 gpm, 5 gpm, 3 gpm, and 1.7 gpm. These discrete levels were attained by controlling the total flow rate in the AC/Htr loop by using a throttling/bypass valve arrangement.

From the data generated during the special air conditioner tests, a new logic system was designed. This system was designed to allow a substantial margin of safety to avoid air conditioner damage while improving the ratio of energy absorbed by the collector subsystem to energy required to drive the air conditioner. Figure III-8 is a schematic representation of the new logic system. Using special air conditioner test data along with the new logic system diagram, a new system performance map was determined as shown in Figure III-9. This map depicts expected values of Q_{gen}, Q_{AC}, and COP as they vary with hot water inlet temperature.

The new logic system incorporates three separate control loops. The basis of the new system is termed the "minimum energy" loop. This uses the two existing air conditioner bypass valves, MV-4 and MV-5 (Fig. II-9), to bypass flow around the air conditioner at high temperatures. Bypassing suppresses heat transfer in the generator, thereby conserving energy. Below 193° F, the full flow rate capability is used to assure the maintenance of percolation in the air conditioner. Below 188° F, the calrod heaters are activated in steps to maintain a minimum generator inlet temperature of 188° F. From 193° F to 203° F, the flow rate through the air conditioner generator is reduced

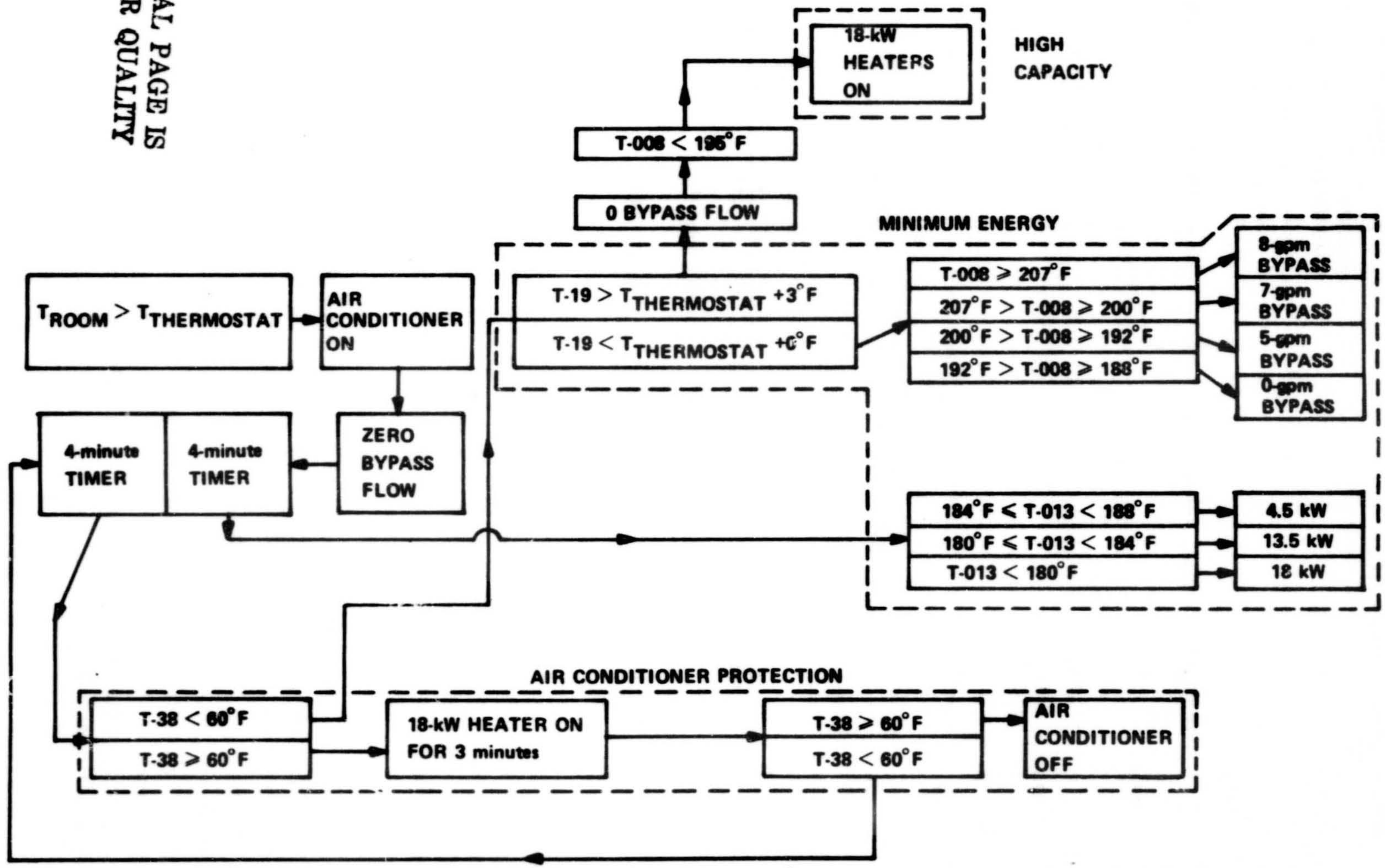

Figure III-8. New air conditioner logic system.

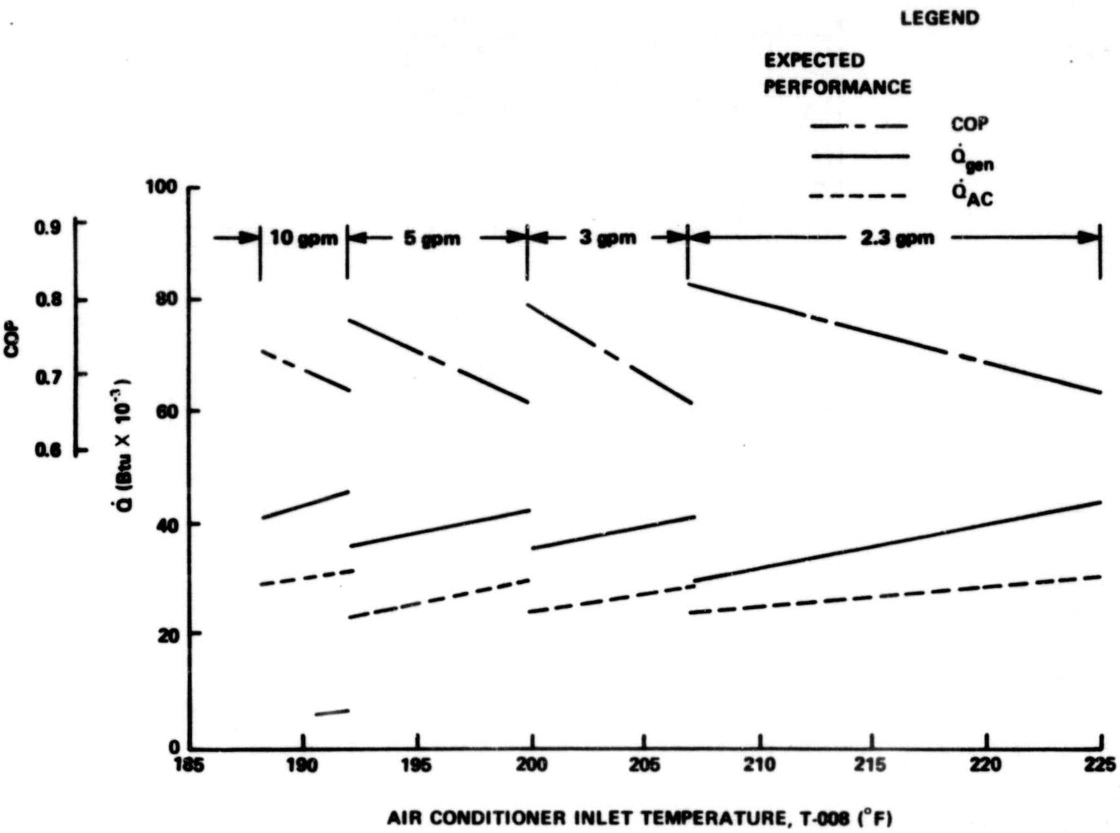

Figure III-9. New logic system performance.

to 5 gpm (i.e., MV-4 open and MV-5 closed). From 203° F to 207° F, the flow rate through the generator is 3 gpm (i.e., MV-5 open and MV-4 closed). Above 207° F, both MV-4 and MV-5 are open, lowering the generator flow rate to the lowest value used of 2.3 gpm. (Note: Special air conditioner tests were run at 1.7 gpm since the exact value of the flow rate with both valves open was unknown.)

The air conditioner protection loop provides protection from conditions in which sustained operation in the "minimum energy" loop is not possible or is marginal. The air conditioner evaporator case temperature, being the most direct indication of proper air conditioner operation, is used to detect improper air conditioner performance. This temperature was redlined so that at values above 60° F full auxiliary heater power is activated to allow the air conditioner the best chance to start. Should the air conditioner fail to run with full heater power, an automatic shutdown is activated. This shutdown opens all air conditioner circuit breakers until manual reset is accomplished. Should the air

conditioner successfully start, then the normal "minimum energy" loop is entered. Any time the 60° F evaporator maximum temperature is violated, the "protection" loop is again engaged.

Should the room temperature at any time rise more than 3° F above the thermostat set point, the "high capacity" loop activates. This loop forces full hot water flow through the generator; if T-008 is above 195° F, this is the sole operation performed. Should T-008 be below 195° F, full heater power is applied. This loop is designed to assure that the maximum cooling capability is being obtained from the unit when the inside temperature is excessively high. When the house temperature drops back to the thermostat setting, this loop is deenergized and the normal "minimum energy" loop is reacquired.

G. Thermal Energy Balance

An examination of the test system shows that an overall thermal energy balance or imbalance is one of the most meaningful indicators of how well the system has performed. In theory, the optimum system should collect sufficient energy to operate the air conditioner and overcome all thermal losses. In reality, a cooling system of this type has not been perfected. Under the heading of energy used falls $\dot{Q}_{gen}$, the thermal energy required to operate the air conditioner, and the system heat leak, Q_{loss}. The energy supplied is that which is collected. This may either be supplied directly to the air conditioner from the collector during the day of collection, Q_{col}, or extracted from the energy storage tank, $Q_{egy\ tk}$, which stores energy previously collected. (Note: A negative sign is applied to $Q_{egy\ tk}$ when it supplies energy to the air conditioner since this results in a tank temperature drop.) When insufficient energy is available at temperatures required to drive the air conditioner, the auxiliary heaters, $Q_{aux\ htrs}$, must supply this shortfall. Considering all these energy sources and sinks, a total system energy balance may be writter to determine the energy loss, Q_{loss},

$$Q_{loss} = Q_{col} - Q_{egy\ tk} + Q_{aux\ htrs} - Q_{gen} \quad .$$

Evaluation of test data established that before the control system modification the average energy collected was 194 000 Btu/day, including days lost to inclement weather. The average value of Q_{gen} was 479 846 Btu/day. Using these values along with the average calculated heat loss per day of 136 315 Btu/day results in an average daily energy shortfall of 422 161 Btu/day. Similarly, the average Q_{col}, Q_{gen}, and Q_{loss} for postmodification days are 395 226 Btu/day, 532 464 Btu/day, and 202 906 Btu/day. These data indicate an average daily shortfall of 340 144 Btu/day, an obvious improvement in the total energy balance. This improvement is even more dramatic when it is considered that the dates in August for which postmodification test data were accumulated were warmer than the premodification June dates; consequently, there were longer daily air conditioner run times. A more meaningful comparison of energy used by the air conditioner is given by $\dot{Q}_{gen}$. The premodification average value of $\dot{Q}_{gen}$ was 55 926 Btu/hour versus 34 621 Btu/hour for the postmodification days. However, considering only this parameter is misleading since the cooling rate provided by the modified system is, in general, less than that of the older system. Air conditioner performance is best assessed using average values of COP determined from daily values. Before the major logic system modification these values averaged 0.59 and after modification they averaged 0.70. These comparisons indicate a significant improvement.

IV. CONCLUSIONS

The successful operation of the MSFC house has demonstrated the technical feasibility of using solar energy for cooling. Although hardware problems were experienced, indications are that solutions to all these problems lie within existing technological capabilities.

Thermal and electrical system performance was discussed in Section III. Daily thermal performance can be assessed by examining the percent of total air conditioner thermal energy supplied by the solar collector subsystem. Table IV-1 summarizes the average values of the most pertinent parameters for initial and final system configurations. A comparison of these values serves to dramatize the improvements realized from the discussed modifications.

Table IV-1 gives the current average energy split as 38 percent solar and 62 percent auxiliary power. These averages are somewhat misleading in that they represent actual measured values for the environment to which the MSFC house was subjected from late July to the first of September. In this period, for the test days considered, approximately 40 percent were significantly overcast (i.e., approximately 3 days per week overcast, little or no sun). This compares with only 25 percent of the days being overcast (approximately 1.5 days per week) from late May to late June. With more favorable climatic conditions the percent of solar energy improves. For instance, the average energy collected on a clear day (using data for August) was 554 424 Btu/day with an average Q_{gen} for these days of 568 600 Btu/day. Using this and assuming 6 clear days and 1 overcast day (zero collection), with an average daily loss of 180 000 Btu, the split would have been 56 percent. For 5 clear days in a 7-day period it would have been 47 percent. Since 3 cloudy days out of 7 represents an unusually high frequency of overcast days for this locale, it is conjectured that a 50-percent split would be a more representative performance estimate for the current system given typical weather conditions for summer operation.

Preliminary evaluation of data accumulated during winter operation for the heating mode indicates that the system provides nearly 100 percent of the thermal energy required for heating.

The currently demonstrated average energy split can be vastly improved. A number of methods that may be used to accomplish improvements are:

- Increasing the collector surface area.

- Modifying the collector design to improve collection efficiency.

TABLE IV-1. AVERAGE SYSTEM PERFORMANCE

	Air Conditioner Energy Consumption Rate (Btu/hour)	Air Conditioner Cooling Rate (Btu/hour)	Coefficient of Performance	Collection Rate (Btu/day)	Percent Solar
Initial System (May 28 to May 31)	71 453	30 010	0.42	231 953	15
New Logic System (July 29 to September 1)	34 621	22 956	0.70	371 192	38

- Advance the absorption air conditioner state-of-the-art by lowering the generator hot water operating temperature.

- Lowering the average air conditioner energy consumption rate by improving the control system.

- Modifying the energy storage tank and line routing to decrease the collector fluid supply temperature.

- Reducing auxiliary equipment power requirements by optimizing the total system.

The large number of possible improvements in itself suggests that significant advances may be realized in the future.